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Buzz Aldrin, *Apollo 11* moonwalker, would like a word with you.

You Promised Me Mars Colonies. Instead, I Got Facebook.

We've stopped solving big problems.
Meet the technologists who refuse to give up. p26

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From the Editor

We look different. What's changed?

Readers hope that redesigns should work and flatter their eyes. They worry that things they liked have been lost, and they dislike additions at odds with their sense of a publication.

Rest assured. The changes are meant to enhance your experiences. We've taken away nothing except a small section called "From the Labs," a not-very-useful summary of recent academic publications. We added "MIT" to "Technology Review," because our authority derives in part from our ownership by the world's leading technological institution.

Rather than writing about fonts and graphic design, or about the navigation of different sections (which I hope is self-evident), let me tell you what we believe, care about, and hope to do.

Name a problem. Any will do: pick one from the section beginning on page 26. We believe that for any big, difficult problem, technology is at least part of the solution. At the same time, new technologies are providing entrepreneurs and businesses with opportunities that can grow prosperity and expand human possibilities.

We're not uncritical boosters of new technologies, recognizing that any revolution has losers as well as winners; but we are disposed to think technology a powerful force for good.

Ours is a technological civilization. Given the number and urgency of the world's problems, it has never been so important to understand how technologies can overcome apparently intractable difficulties. It has never been so important to understand how technologies can overturn existing markets and create entirely new ones.

Yet no earthly activity is so badly served by the journalism that seeks to explain it. Nothing humans do is so obscured by hyperbole, jargon, and inaccurate reporting. Technology matters, but you can't understand it by reading most technology sites and magazines. We want to change that by applying an authoritative filter to the overwhelming flood of information about technology.

We're committed to informing our readers about important new technologies by explaining the practical impact of these advances, describing how the technologies work and how they will change our lives. Our main criterion in choosing what to write is our judgment as to what will best serve our audiences. To fulfill our mission, we make accuracy and independence our highest priorities. We do everything in our power to publish correct information. Our coverage is independent of any corporate relationships, including our ownership by MIT, or any business arrangements, such as agreements with advertisers.

We mean to publish smart, literate, originally reported journalism and useful information in a variety of beautifully designed media, both digital and print; we want to produce thought-provoking events that make that journalism live and breathe on stage; and we hope to provide the world with a badly needed example of an innovative, commercially sustainable, digitally oriented global media company.

We've been doing something like this since 1899, when MIT began publishing *The Technology Review*. But starting today, we're going to do it better, with more impact, and in new ways. We want to lead the global conversation about new technologies because nothing is more important.

Write to me and tell me what you think of our designs at jason.pontin@technologyreview.com.

MARK OSTOW

Contents

Front

Big Solutions
ISSUE

Has technology failed us? Over a billion people still have no electricity, millions lack clean water, education is inaccessible to many, the climate is changing rapidly, traffic snarls cities, and dementia and cancer can strike any of us. In this issue we'll introduce you to the technologists who haven't given up trying to solve problems like these.

Back

ON THE COVER: Buzz Aldrin photographed by Dan Winters for *MIT Technology Review*

GROOMING BY DARCY GILMORE; STYLING BY SARAH BRAM

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MIT Technology Review identifies the new technologies that matter—explaining how they work, deciphering their impact, and revealing how they'll change our lives. Founded at the Massachusetts Institute of Technology in 1899, we are a digitally oriented global media company that publishes serious journalism in magazines and on websites and mobile devices. We also host events around the world. Technology Review, Inc. is an independent nonprofit 501(c)(3) corporation wholly owned by MIT; the views expressed in our publications and at our events are not always shared by the Institute.

De Technologia non multum scimus. Scimus autem, quid nobis placeat.


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Feedback

WHY CHEAP NATURAL GAS IS GOOD, AND ALSO TERRIBLE

In our last issue, editor David Rotman (in his review "King Natural Gas") examined how a glut of natural gas is hindering green energy. Putting a price on carbon dioxide is often suggested as a way to boost green energy, but the review noted that natural gas is now so cheap it could be offset only by a carbon price that is too high to be politically viable. This annoyed **Neil Frazer**, a geophysics professor at the University of Hawaii at Manoa: "I'm tired of hearing economists saying that a carbon tax isn't politically feasible. Their job, surely, is to tell us what would work, not whether it is politically feasible. Taxes on alcohol and tobacco were both politically infeasible before they were enacted."

One online commenter, **intarz**, lamented the lack of ingenuity when it comes to clean energy: "I would hate to see a bust in the wind area. I just drove out west and the number of wind farms in Iowa, Nebraska, Wyoming, Colorado, and Kansas is staggering. But scattered wind farms will never be effective as long as the industry wants to distribute the power through lines. They should think of alternative distribution schemes. Trains loaded with batteries. Can the electrolyte be charged and pumped in plastic lines from the charging source to the decharging point? I don't have the answers, but I am surprised the industry seems to consider it efficient to produce power on the plains but ignores the cost to distribute it."

JOIN THE DISCUSSION, OR CONTACT US

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Please include your address, telephone number, and e-mail address. Letters and comments may be edited for both clarity and length.

Rajat Sen, another online commenter, felt the new glut of cheap fossil fuels was fine, but we shouldn't dupe ourselves into thinking it will last forever. "Shale oil and gas are changing our energy economy for the better. Some say these resources can last as long as 100 years, while other estimates are much lower. No matter which side is correct, the resources are limited. They do give us some breathing room to develop sensible energy policies and develop new technologies that are less harmful to the environment. We should use that time wisely."

THE INTERNET IS ABOUT TO GET CONFUSING

ICANN, the body that oversees Internet domains, wants to make all sorts of new domains available: instead of just .com, .net, and so forth, it wants to consider the likes of .book, .restaurant, and .carinsurance. Writer Wade Roush took a critical look at the possibilities (in his review "ICANN's Boondoggle") and saw a world of confusion and greed. Many readers agreed. "The apologists of this new program are happy to use words like competition and choice," wrote **Dylanj** in an online comment. "However, you'll notice that most of the rhetoric comes from those who stand to directly benefit from it. When you see all those involved in the program, they are seldom people who seem genuinely there for a good cause. Instead, you see smart people working hard to ensure they make a lot of money while producing almost no real value to the Internet ecosystem and probably a lot of unnecessary confusion."

Natcohen was similarly bothered: "For whose benefit is ICANN overseeing the Internet? The main beneficiary of ICANN's decisions seem to be—big surprise—ICANN itself. Is ICANN responding to a huge public clamor for more domain extensions? No. They just decided to create huge new territories on the Internet and auction off the rights to that territory, keeping all the money for themselves."

Not everyone is outraged, however. "The basic premise of this article is all wrong," wrote **Tom Barrett** in an online comment. "Who are you or anyone else to decide if there is a good reason for the Internet expansion? We should be encouraging startup activity, not trying to hold it back."

YOU CALL THESE PEOPLE INNOVATORS?

Our September issue featured our annual list of "35 Innovators Under the Age of 35." **Gary Calabrese** of Corning, New York, wrote to say that although he enjoyed the feature, he had a quibble with our use of the term "innovator." "Although all of these folks are certainly very creative and inventive, many cannot be declared 'innovators' until their inventions deliver tangible economic or societal value. The promise of a breakthrough from an idea or even a patentable invention does not make it an innovation until someone somewhere actually finds it valuable enough to use."

As for our Entrepreneur of the Year, Ren Ng, creator of a camera whose images can be refocused even after the shot has been taken, one commenter, **Mahonj**, felt the innovation in question was a neat trick

with little practical value: "While the technology is impressive, I think Dr. Ng has solved a problem that didn't need to be solved. I have never heard people fuming about photographs focused on the wrong object. In fact, most real photographers want to limit the range of focus by using fast lenses and large, SLR-sized sensors. That is what you read about on the camera websites. The technology may be impressive, but the results aren't compelling. Focusing on the flower or the mountain is a party trick. It doesn't fulfill a real need."

THE ROBOTS ARE READY TO SERVE YOU NOW

OUR BUSINESS REPORT on automation investigated all the ways that machines are transforming how we do business. **Eugene Chuvyrov**, in an online comment, wondered if our senior business editor, Antonio Regalado, was overstating the case in his introductory essay, "Automate or Perish." "I program machines for a living," Chuvyrov wrote, "and I do not believe in the singularity, nor do I believe in the economy being a zero-sum game (machines win, humans lose). In fact, the promises of AI have largely remained unfulfilled. Can you really trust Siri, or reliably use Google Translate for more than a six-word sentence? I think we have quite a ways to go before the Terminator days. I suspect the lack of job growth in recent years has a lot more to do with political issues than with automation ones."

Another commenter, **Qev**, wondered where all this was leading: "Throughout history, the natural response to displacement (in this case due to automation) was large-scale human migration. But where on earth (or in space, for that matter) is there a place where the tasks or operations still require a large pool of living, breathing, self-aware humans?" T

Views

Gary Small

Kara Kockelman

Larry Brilliant

HEALTH

Alzheimer's Ahead

An epidemic of age-related dementia looms, says Gary Small.

Every 68 seconds, another American is diagnosed with Alzheimer's disease. The coming wave of older people with dementia will place an unprecedented emotional and economic burden on society (see "The Dementia Plague," p. 50). We're living longer thanks in part to advances in medical technology, but we're not necessarily living better.

Approximately 80 million baby boomers are beginning to approach the years when symptoms of Alzheimer's disease emerge. The risk for those 65 and older is 10 percent, and it nears 50 percent by age 85. A report on the global economic impact of dementia by Alzheimer's Disease International estimated the 2010 costs of care at $604 billion.

We are wholly unprepared for this crisis.
Gary Small

We are wholly unprepared for this crisis. Despite decades of research, we have no cure, nor even any drug that can reverse or stave off symptoms more than temporarily. Considerable effort has targeted the plaques of amyloid protein that form in the brains of Alzheimer's patients, but none of the latest clinical trials have succeeded. Though we must continue to explore amyloid's contribution, we also need to research more widely, because there is more to Alzheimer's disease. Efforts need to be made to investigate treatments that target other potential mechanisms, such as abnormal accumulation of brain tau protein and inflammation of neurons. Resources need to be found for work on drugs or vaccines that protect a healthy brain before it becomes damaged. Many research groups, including my own, have developed brain scans and other tests that can detect the disease years before dementia develops.

We cannot afford to wait for new treatments, with their long development times. We should act now on compelling evidence that lifestyle choices such as diet and cardiovascular conditioning can forestall dementia symptoms. For example, two key Alzheimer's prevention strategies, diet and exercise, are known to prevent type 2 diabetes, which doubles the probability of developing Alzheimer's dementia.

If society is to avoid being overwhelmed by the cost of the Alzheimer's epidemic, the disease must become an international health priority. Yet we have not invested as much in fighting it as we have in combating other diseases. Recent findings from the U.K. support increasing Alzheimer's research funding by a factor of 30 to reach parity with cancer research. Making such an investment to catch up will pay off by saving millions of lives and, eventually, trillions of dollars.

Gary Small is director of the University of California, Los Angeles, Longevity Center.

TRAFFIC

Curing Congestion

We can now tackle traffic as a complex network problem, says Kara Kockelman.

Over half the world's population and 80 percent of Americans live in urban areas, where land for new transport infrastructure is relatively scarce. Most roads have no tolls, and most vehicles carry a single occupant. Not surprisingly, road congestion has become a daily experience for many.

ANDY FRIEDMAN

Globally, people average about 60 minutes of travel each day, much of that consumed by stops or slowdowns. Some delays are regular and recurring, others unexpected. They are all more than just a personal inconvenience: human capital is underutilized, freight distribution delayed, meetings missed, fuel wasted, and nerves frayed.

Many important roadways regularly operate near their breaking points, and as populations and economies continue to expand, travel demands will rise and waits lengthen. Stressed transportation systems become less resilient and create cascades of real costs. As freight is slowed, food prices rise, for example; and as travel times exceed acceptable thresholds, certain destinations lose their attraction.

Thanks to new technologies we are now able to observe these systems and congestion's effects in real time, across the large, complex scales at which they operate. We are also able to intervene at the same scale, not just locally, an approach that raises the prospect of making congestion a thing of the past.

Transportation system managers can now turn to a combination of sensors, algorithms, and system simulators to predict traffic demands from minute to minute, day to day, and year to year. In a highly instrumented system like New York City's, signal times, tolls, and left-turn permissions can be fine-tuned in real time.

Truly reducing, rather than just managing, congestion requires active intervention to change travelers' behavior and make the most of scarce roadway real estate. Varying tolls throughout the day in response to traffic patterns, offering slot reservations for space in some lanes, and compensating those who turn to alternatives to their own vehicle are one set of options. GPS-enabled smartphones and other technologies make such strategies much more realistic, since drivers can receive and act on information rapidly. The arrival of autonomous, self-driving vehicles that can safely travel close together should make it even easier to enhance traffic flow (see "Self-Driving Cars," p. 41).

Many roadways operate near their breaking points.

Kara Kockelman

With road space limited, over the long term travelers will need to shift to smaller vehicles, public transit, and nonmotorized modes of transport. But by acknowledging the true costs and complexity of road congestion, we can moderate it quite effectively now.

Kara Kockelman is a professor of transportation engineering at the University of Texas, Austin.

INFECTIOUS DISEASES

Repeating History

We have fully eradicated only one disease. Let's do it again, says Larry Brilliant.

In human history, few things happen only once. Over millennia, even statistically rare events repeat. Yet despite huge efforts to replicate the feat, just once have we eradicated a human disease: smallpox, responsible for over 500 million deaths in the 20th century alone.

Eradicating smallpox was a technological and a human challenge, like many of our toughest global problems (see "Why We Can't Solve Big Problems," p. 26). Technology made it possible to develop freeze-dried vaccine and the bifurcated needle. Hundreds of thousands of humans had to find every case of smallpox in the world, village by village, house by house, and vaccinate every single person exposed to the virus. I was on the smallpox team in India and Bangladesh in the 1970s, and we made over one billion house calls.

Today, we're close to finally repeating that achievement: polio now circulates in only three countries. But new diseases keep surfacing. Over the last two decades, around 30 have crossed from animals to humans, including SARS and hantavirus. Modernity has increased the risk of a global pandemic. Growing populations and economies lead to deforestation and greater consumption of meat, including bush meat, which increase the likelihood of a virus jumping from animals to humans. Air travel gives viruses free transit across oceans in hours.

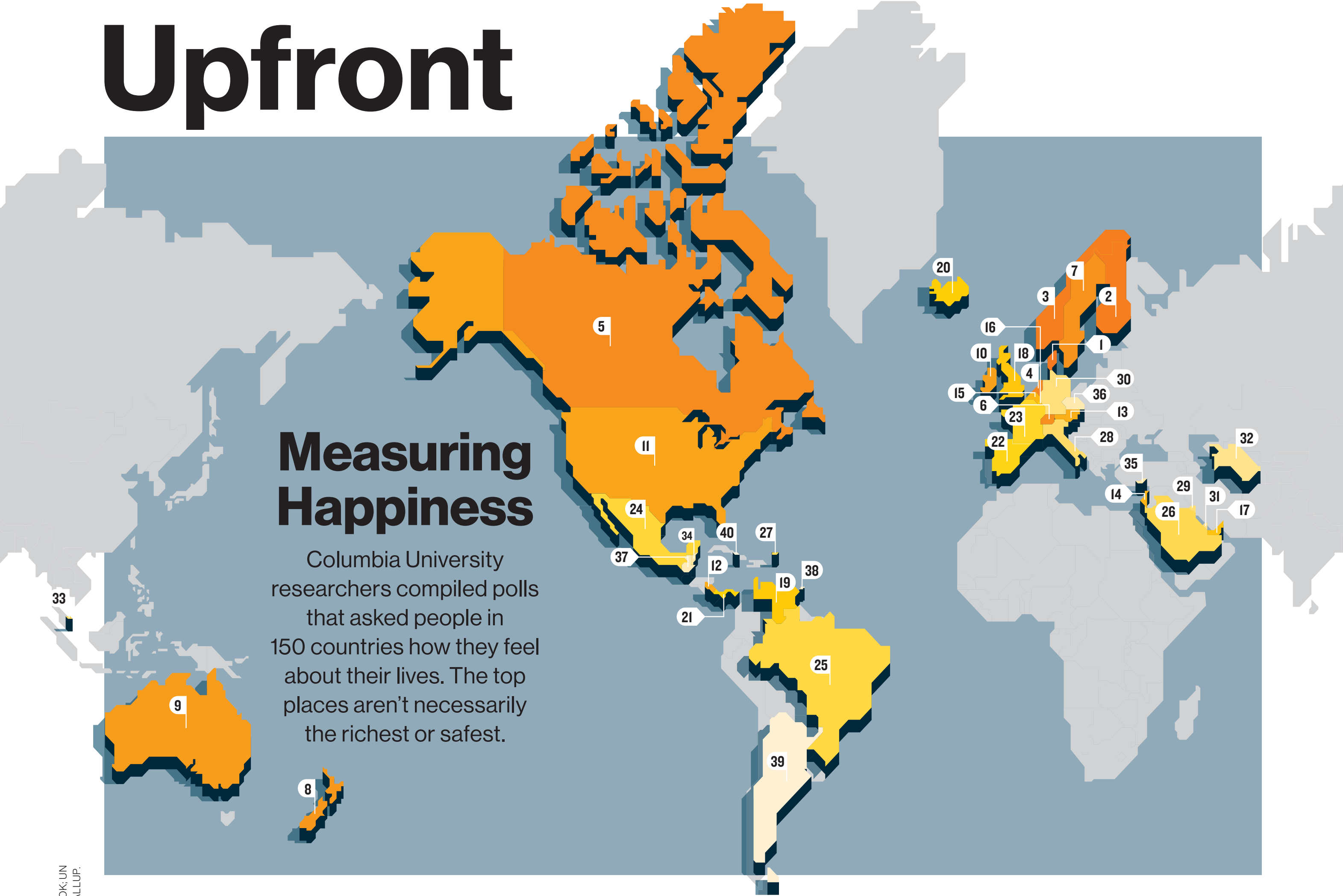
Modernity is also the balm for this ailment. Since 1996, the median time it takes to detect a disease outbreak has fallen from 30 days to 14 days. Digital disease surveillance has greatly improved our ability to find diseases early enough to stop them from spreading.

The first systems to collect "cloud" data on emerging diseases used e-mail, like ProMed, or scoured the Web for evidence, like GPHIN. We can now gather data directly from people exposed to disease. Google's Flu Trends experiment proved that analyzing how people search for information about flu online beats Centers for Disease Control reporting by up to two weeks. At the Skoll Global Threats Fund we are working on an initiative, Flu Near You, that asks people to answer questions about symptoms via Web or smartphone. That kind of participatory surveillance on mobile devices could help track and tackle diseases around the world.

We now have so much more technology than we did when smallpox was eradicated. We can solve this problem without making a billion house calls. All we need is creativity, commitment, and public will.

Larry Brilliant is president of the Skoll Global Threats Fund, a nonprofit identifying and addressing large-scale risks to humanity.

Upfront



Measuring Happiness

Columbia University researchers compiled polls that asked people in 150 countries how they feel about their lives. The top places aren't necessarily the richest or safest.

The 40 happiest places

1 Denmark	6 Switzerland	11 United States	16 Luxembourg	21 Panama	26 Saudi Arabia	31 Qatar	36 Czech Republic
2 Finland	7 Sweden	12 Costa Rica	17 U.A.E.	22 Spain	27 Puerto Rico	32 Turkmenistan	37 Guatemala
3 Norway	8 New Zealand	13 Austria	18 United Kingdom	23 France	28 Italy	33 Singapore	38 Trinidad & Tobago
4 Netherlands	9 Australia	14 Israel	19 Venezuela	24 Mexico	29 Kuwait	34 Belize	39 Argentina
5 Canada	10 Ireland	15 Belgium	20 Iceland	25 Brazil	30 Germany	35 Cyprus	40 Jamaica

Per capita GDP, in U.S. dollars

1. Qatar (ranks 31st in happiness) $104,300
2. Luxembourg (16) $81,100
3. Singapore (33) $60,500
4. Norway (3) $54,200
5. Hong Kong (67) $49,800
6. United States (11) $49,000
7. United Arab Emirates (17) $48,800
8. Switzerland (6) $43,900
9. Netherlands (4) $42,700
10. Austria (13) $42,400

Life expectancy, in years

1. Japan (ranks 44th in happiness) 83.91
2. Singapore (33) 83.75
3. Hong Kong (67) 82.12
4. Australia (9) 81.9
5. Italy (28) 81.86
6. Canada (5) 81.48
7. France (23) 81.46
8. Spain (22) 81.27
9. Sweden (7) 81.18
10. Switzerland (6) 81.17

Fewest murders per million people

1. Hong Kong (ranks 67th in happiness) 2
2. Singapore (33) 3
3. Iceland (20) 3
4. Japan (44) 4
5. Norway (3) 6
6. Austria (13) 6
7. Bahrain (61) 6
8. Slovenia (49) 7
9. Switzerland (6) 7
10. Germany (30), Spain (22), U.A.E. (17) 8

GRAPHIC BY WALTER C. BAUMANN. DATA FROM THE EARTH INSTITUTE, COLUMBIA UNIVERSITY; CIA WORLD FACTBOOK; UN OFFICE OF DRUGS AND CRIME. TOP-10 CHARTS EXCLUDE COUNTRIES THAT WEREN'T AMONG THOSE POLLED BY GALLUP.

Upfront

QUOTED

"We should be able to travel instantly and not just as a voice or a screen on the wall."

—Scott Hassan, founder of Suitable Technologies, a company that is selling a $16,000 telepresence robot for office workers.

Artificial Intelligence, Powered by Many Humans

Crowdsourcing can create an artificial chat partner that's smarter than Siri-style personal assistants.

By Tom Simonite

Automated assistants such as Apple's Siri may be useful, but they don't have nearly the smarts or conversational skills of a person. Now researchers have demonstrated a potentially better approach that creates a smart chat partner out of fleeting, crowdsourced contributions from many workers.

Crowdsourcing typically involves posting simple tasks to a website such as Amazon Mechanical Turk, where Web users are paid a few cents each to complete them. The tasks are often simple, repetitive jobs that are easy for humans but tough for computers, such as categorizing images. Crowdsourcing has become a popular way for companies to handle such tasks, but some researchers believe it can also be used to take on more complex ones.

When a person opens an instant messaging window using the new crowd-powered system, which is called Chorus, the experience is practically indistinguishable from that of chatting with a single real person. Yet behind the scenes, each response emerges from the work of multiple people all performing individual small tasks, including suggesting possible replies and voting for the best suggestions submitted by other workers.

In tests, Chorus was asked for travel advice and came up with smarter responses than any one person in the crowd, because around seven were contributing to its responses at any time. Services built this way might also be cheaper than paying a conventional one-on-one assistant. "It shows how a crowd-powered system that is relatively simple can do something that AI has struggled to do for decades," says Jeffrey Bigham, a member of the team that created Chorus at the University of Rochester. Bigham jokes that Chorus is more likely than conventional chat software to pass a →

JON HAN; COURTESY OF SCOTT HASSAN

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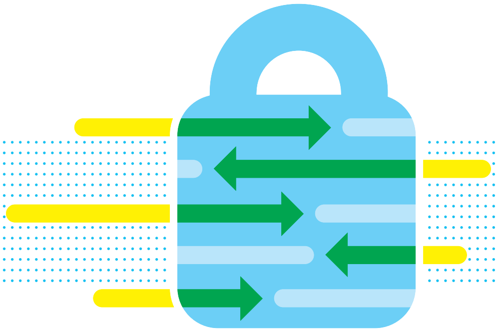

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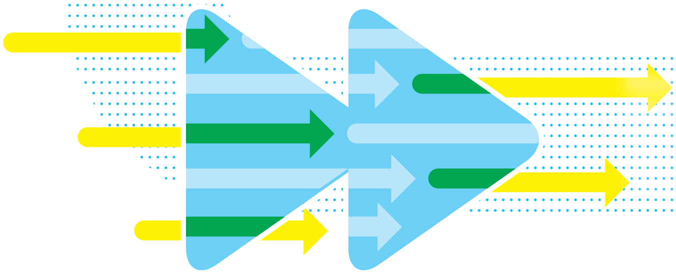

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Upfront

Turing test, which challenges an artificial-intelligence system to fool someone into thinking it's human, even though Chorus wouldn't meet most definitions of artificial intelligence.

In trials of the system, people quickly received suggestions when they asked for advice on restaurants to visit in Los Angeles and New York. Feedback such as "Hmm. That seems pricey" was quickly taken on board by the crowd, which came up with alternatives. AI systems such as Siri typically have difficulty following this kind of back-and-forth conversation, particularly in colloquial language.

Bigham worked with Rochester colleagues Walter Lasecki and Rachel Wesley as well as Anand Kulkarni, cofounder of the crowdsourcing company MobileWorks. "What we're really interested in is when a crowd as a collective can do better than even a high-quality individual," he says.

The intelligence of Chorus comes from combining different people's work on many simple tasks into a coherent whole. First, each piece of a chat entered by a human user is passed along to many crowd workers, who are asked to suggest a reply. Those suggestions are then voted on by crowd workers to choose the one to be sent back. A final mechanism creates a kind of working memory to ensure that Chorus's replies reflect the history of a conversation, crucial if it is to carry out long conversations—something that is a challenge for apps like Siri. Crowd members are asked to maintain a running list of the eight most important snippets of information discussed, to be used as a reference when other workers suggest replies. "A single person may not be around for the duration of the conversation—they come and go, and some may contribute more than others," says Bigham.

Bigham says Chorus has the potential to be more than just a neat demonstration. "We want to start embedding it into real systems," he says. "Perhaps you could help someone with cognitive impairment by having a crowd as a personal assistant," he suggests. Such an assistant would always be on hand, ready to answer a question.

Another possibility is to combine Chorus with a system previously developed at Rochester, which has crowd workers collaborate to steer a robot. "Could you create a robot this way that can drive around and interact intelligently with humans?" asks Bigham.

Michael Bernstein, an assistant professor at Stanford University who is currently doing research at Facebook, agrees that Chorus could lead to real-world applications. "You could go from today, where I call AT&T and speak with an individual, to a future where many people with different skills work together to act as a single incredibly intelligent tech support," he says. He believes the Chorus software could become a true expert if it were able to direct incoming questions to members of the crowd with particular knowledge or skills.

"What we're really interested in is when a crowd as a collective can do better than even a high-quality individual."

However, Bernstein adds that it may be necessary to add more reviewing steps to Chorus in order to filter a crowd's suggestions, so that it does not develop a split personality when faced with difficult questions. This is a familiar problem in applying crowdsourcing. For example, when the Rochester researchers built their crowd-controlled robot, one of the biggest challenges was preventing it from crashing into obstacles dead ahead because half the crowd steering it wanted it to go left and the other half wanted it to go right.

QUOTED

"One of my initial reactions was 'Are you kidding?'"

—Roel Schouwenberg, a computer security researcher at Kaspersky, referring to the finding that malware known as Mahdi, despite being sloppily designed, had infiltrated banks, governments, and companies that operate critical infrastructure.

TO MARKET

Magic Book

Wonderbook: Book of Spells

COMPANY: Sony

PRICE: $39.99 standalone or $79.99 with PlayStation Move hardware

AVAILABILITY: November

This video game for the PlayStation3, based on J.K. Rowling's Harry Potter series, combines augmented reality with gesture control so that players appear to be wizards casting spells. When the players hold up the pages of a book with specially marked paper, the PlayStation Move system captures their movements; these are translated into animated on-screen images. For instance, the system's stick-like controller appears on screen to be a magic wand. Sony plans to use the same technology in other new releases. Games with dinosaur and detective themes, among others, are now in the works.

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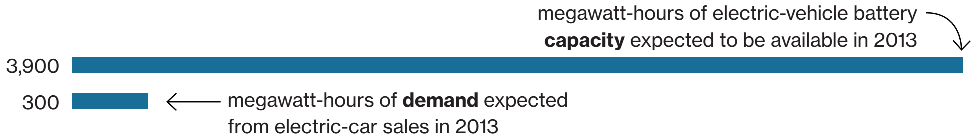
Upfront



New Tests Could Divine a Baby's Genome Before Birth

Blood tests may herald a new wave of noninvasive prenatal screening.

By Courtney Humphries

Expectant mothers are used to blood tests to screen for potential health problems in their unborn babies. But what if one of those blood tests came back with a readout of the baby's entire genome?

Recent studies show that it's possible to decode a complete fetal genome from a sample of the mother's blood. In the future, doctors may be able to divine a wealth of information about genetic diseases or other fetal characteristics this way. Such tests will raise ethical questions about how to act on the information. But they could also lead to research on how to treat diseases before birth, and they could leave parents and doctors better prepared to care for babies after birth.

It's been about 15 years since Dennis Lo, a chemical pathologist at the Chinese University of Hong Kong, first discovered that fragments of DNA from a fetus could be found in a pregnant woman's blood. The work was a breakthrough, since obtaining fetal DNA from the amniotic fluid, from the placenta, or directly from the fetus's blood requires an invasive procedure that raises the risk of miscarriage. A noninvasive test would make genetic testing safer and much more widely accessible.

Since then, several labs have worked to analyze this fetal DNA and exploit it for noninvasive prenatal tests. The field has progressed rapidly in the past couple of years as genetic sequencing technologies have become vastly cheaper and faster while methods of analyzing genetic data have improved.

One of the first tests to be developed is for RhD factor, a type of blood protein; if the mother is RhD negative and her fetus is RhD positive, the incompatibility can be dangerous or even fatal for the fetus. Sequenom, a company that licensed Lo's research, began offering a noninvasive RhD test in 2010. Several companies have also offered tests for sex determination and paternity.

But what has gained more attention is a recent wave of tests to detect Down syndrome, which is caused by an extra copy of chromosome 21. Women in the United States are routinely offered screening for Down syndrome, so the market for such a test is large.

Typically, a pregnant woman receives an initial screening for substances in her blood associated with Down syndrome. Jacob Canick, a professor of pathology and laboratory medicine at Brown University, explains that the tests detect 90 percent of Down syndrome cases but have a false positive rate of 2 to 5 percent. Invasive tests such as amniocentesis are the only way to make a definitive diagnosis. Given that Down syndrome affects only one in 500 pregnancies, the number of women with a false positive is much higher than the number truly carrying an affected fetus. "That means that 19 out of 20 women who undergo an invasive procedure will find out that they don't have the genetic abnormality," Canick says.

With those low odds, many women opt against the invasive procedure. But new noninvasive tests could make accurate screening much more widespread. "It seems, from our data and other data, that these tests are very, very good," says Canick, who led a trial, funded by Sequenom, on one of these tests.

Several startups have begun offering fetal tests for Down syndrome and other health problems caused by extra or missing chromosomes. But the speed with which the tests have made their way into doctor's offices has some people concerned. "There's not a minimum standard of accuracy that's required before they go to market," says Mildred Cho, a bioethicist at Stanford University. She says that the tests are being adopted even as their accuracy is being evaluated in clinical →

SHANNON MAY; DATA FROM MENAHEM ANDERMAN, ADVANCED AUTOMOTIVE BATTERIES

Upfront

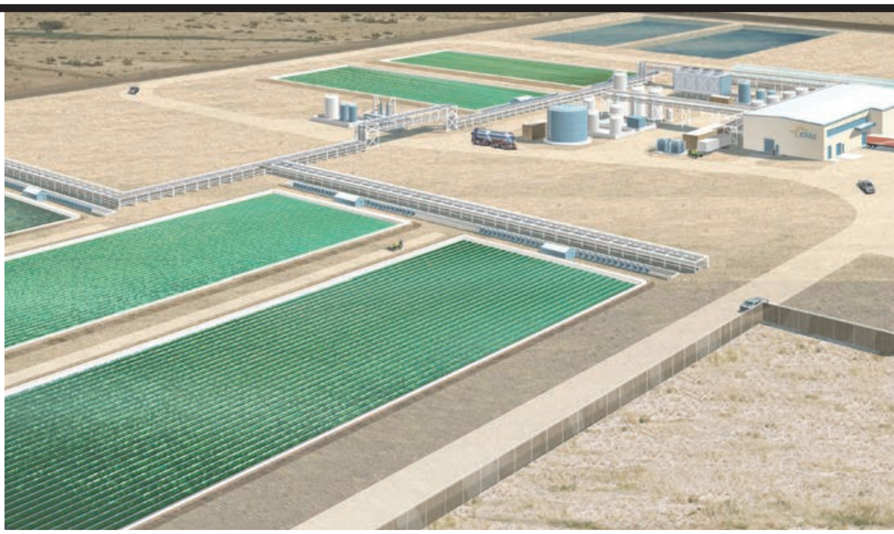
studies. Whereas most prenatal genetic tests have been developed through academic laboratories, this technology was quickly commercialized and disseminated through companies.

Meanwhile, recent studies suggest that noninvasive testing could expand in the coming years beyond simply counting chromosomes to hunting for smaller genetic aberrations, including mutations in single genes. A study published in June by a group at the University of Washington decoded a fetus's genome using a blood sample from the mother and a saliva sample from the father. Meanwhile, Stanford University researchers have accomplished a similar feat using only a blood sample from the mother.

That means parents could soon receive a comprehensive test that could screen for all kinds of genetic abnormalities and characteristics. "When you open it up to whole-genome analysis, that brings up the possibility of testing for traits that are not diseases," says Cho. It also makes it possible to test for diseases that are not as simply determined as Down syndrome.

Diana Bianchi, of the Mother Infant Research Institute at Tufts Medical Center, hopes that the ability to uncover diseases in fetuses will spur a new interest in treating them before birth. "Things that are treatable are really going to change the landscape," she says.

At the New Mexico demonstration plant shown in this rendering, Joule Unlimited expects to make fuel out of sunlight, water, and carbon dioxide.



Driving a Biofuel Forward

Joule Unlimited gets a boost for its novel method of making fuel out of light, air, and water.

By Kevin Bullis

Joule Unlimited, a startup whose engineered microörganisms produce ethanol from sunlight, water, and carbon dioxide, is taking important steps forward. It has a new demonstration plant, and it recently formed a partnership with Audi to develop and test the fuel.

Most biofuels companies make fuel by processing some form of biomass, such as corn, grass, or algae, often with the aid of microörganisms. Joule's approach is to eliminate as many of the intermediate steps as possible.

Joule has taken a microörganism (the company won't say what) and introduced combinations of genes so they produce ethanol from carbon dioxide, water, and sunlight. To ensure that its metabolism is geared toward making ethanol rather than keeping the organism alive, the company has removed as many of its original genes as is possible without killing it.

TO MARKET

Implantable Pain Fighter

Eon Mini Neurostimulator

COMPANY: St. Jude Medical

PRICE: undisclosed

AVAILABILITY: now, in Europe

Patients with severe chronic migraines that do not respond to medication can now seek relief with the world's smallest rechargeable device for neurostimulation. In September, the European health regulatory agency approved the Eon Mini to help patients manage the pain associated with these difficult-to-treat headaches, known as refractory migraines. The device, which surgeons implant under the skin, delivers mild electric pulses to nerves in the back of the head. A company study found that after one year of use, 65 percent of patients reported significant pain relief. The device already has approval in the United States, Europe, and Japan for treatment of chronic back and limb pain.

COURTESY OF ST. JUDE MEDICAL; COURTESY OF JOULE UNLIMITED

In small-scale tests, Joule has shown that its approach could produce 8,000 gallons of ethanol per acre per year, a few times more than other advanced-biofuels companies have achieved. But now as Joule moves its technology to market, the company says it has found more economical methods that have the potential to produce 25,000 gallons of ethanol per acre per year. It's also developing organisms that produce diesel.

Crucial to the new approach are the transparent tubes in which Joule grows the microörganisms. In the company's original design, the containers resembled solar panels—they were flat, thin, and rectangular. Partly to allow air to move over them for cooling, the panels were mounted on metal frames on concrete pads. "We saw very quickly that the design would not be cost-competitive," says David Berry, a partner at Flagship Ventures, which has provided much of Joule's funding.

Joule's solution was to do away with the concrete foundations, metal frames, and solar-panel-like structures and use plastic tubes instead. The tubes are a couple of meters wide and up to 50 meters long. "The new design is much larger, and you can lay it directly on the ground. That leads to a huge reduction in cost," says William Sims, Joule's CEO.

Joule plans to work out the final design for the system at its new four-acre demonstration plant in Hobbs, New Mexico. One challenge other biofuels companies face is that the economics of their processes won't be clear until they are demonstrated in full-scale commercial facilities, with large vats for producing biofuel. Sims says Joule's approach can be validated with just a few of its plastic solar converters, reducing the amount of financing needed. "It's pure replication," Sims says. "What works for four acres will also work for 5,000 acres."

A Solar Startup That Isn't Afraid of Solyndra's Ghost

Braving comparisons to the bankrupt Solyndra, SoloPower is moving ahead with the production of thin-film solar panels.

By Jessica Leber

Last year's bankruptcy of Solyndra, a maker of thin-film solar panels that received a $535 million loan guarantee from the U.S. Department of Energy, is casting a huge shadow over solar startups. But it hasn't stopped SoloPower, another Silicon Valley–based manufacturer of solar panels with a very similar technology. SoloPower recently began production in a manufacturing facility in Portland, Oregon.

Like its failed predecessor, SoloPower has been awarded a federal loan guarantee ($197 million, which was approved during the same month that Solyndra announced bankruptcy), though it hasn't begun tapping into the money. What's more, SoloPower is targeting the same niche market as Solyndra: rooftops of industrial or commercial buildings.

The comparisons go only so far. Solyndra's bankruptcy had more to do with its own business failures than with flaws in its technology. The company spent far too much money far too fast and produced far more product than it had customers for.

Even so, SoloPower is entering production during a horrible time for solar-panel manufacturers, especially for producers of thin-film technology. The technology is meant to be cheaper than conventional silicon-based solar cells, but the plunge in silicon's price has largely negated its advantage.

To avoid Solyndra's fate, SoloPower is going after the half of all commercial and industrial building owners who can't use more conventional solar power because their rooftops can't support the weight of today's modules, says CEO Tim Harris. The company is betting its lightweight product will command a higher price than panels sold as commodities. It will begin by selling in countries, such as Japan and Italy, that have strong demand for rooftop solar, relatively high peak electricity prices, and some government incentives. Says Harris, "We have more demand than we have capacity for the next couple of quarters."

SoloPower's chief technology officer, Mustafa Pinarbasi, shows off the company's flexible solar technology.

COURTESY OF SOLOPOWER/BRUCE MACGREGOR

Upfront

17%

Apple's share of the worldwide smartphone market, according to IDC. Android phones have a 68 percent share.

66%

Apple's share of the worldwide profit generated by smartphone sales, according to Asymco, a research firm.

How Your Wireless Carrier Overcharges You

Bad coverage and streaming video can confuse carriers into making you pay for data you never receive.

By Tom Simonite

When your wireless carrier charges you for the amount of data you used on your cell phone in a given month, how do you know the bill is accurate? It very well may not be, according to a new study.

This question has become important now that the largest U.S. mobile carriers have replaced unlimited data plans with ones that cap data usage and charge extra for exceeding those limits.

Working with three colleagues at the University of California, Los Angeles, computer science PhD researcher Chunyi Peng probed the systems of two large U.S. cell-phone networks. She won't identify them but says that together they account for 50 percent of U.S. mobile subscribers. The researchers used a data-logging app on Android phones to check the data use

the carriers were recording. They were found to count data correctly most of the time, but they tended to overcount—and hence potentially overcharge—when a person used applications that stream video or audio, and particularly when coverage was weak or unreliable.

The researchers determined that even typical use of a phone could lead the data to be overcounted by 5 to 7 percent.

The problem occurs because carriers count off data as it leaves the heart of their networks and heads to the mobile tower nearest a subscriber. That means data is tallied whether a subscriber's phone receives it or not. If a person on a bus is streaming video but enters a tunnel and loses the connection, the unseen video will be counted toward that customer's plan.

The problem affects video and audio streaming apps in particular because they use protocols that don't require the receiving device to acknowledge the receipt of every chunk of data, as Web browsers and many other apps do. That means a video app will keep sending data for some time, oblivious to the fact that a device can't receive it.

Using a custom app made to demonstrate the flaw, the UCLA researchers racked up a charge for 450 megabytes of data they never received. "We wanted to explore how bad it could be and stopped after that," says Peng. "There's apparently no limit."

It should be simple, says Peng, for mobile network operators to change this by adding software to make the phones give some feedback to the central data loggers. But she notes that carriers might say their current accounting is fair, since they incur the costs of transmitting data whether it reaches a device or not. "From the perspective of a mobile user, I think it's not fair," she says, "because I didn't get to use it."

TO MARKET

Reflecting Rays

OptiMax Wave

COMPANIES:
Hanwha Solar/tenKsolar

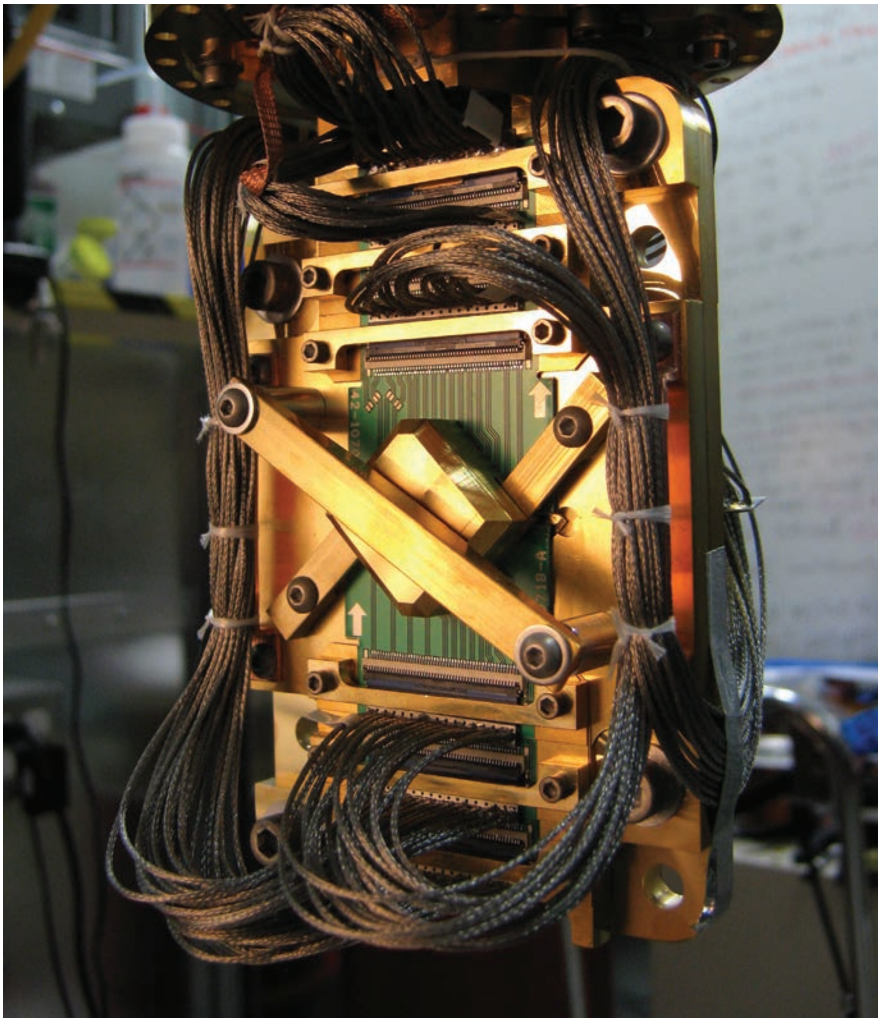
PRICE:
undisclosed

AVAILABILITY:
this fall in the U.S.

To squeeze more energy from solar panels, Korea's Hanwha Solar will sell a system with unique solar-cell wiring and low-cost reflectors. The OptiMax Wave, made by tenKsolar of Minnesota, can boost the electricity generated by solar panels on a flat roof by 30 percent. Inside the panels, solar cells are wired in a mesh-like grid, rather than in series, so current from all the panel's cells isn't constrained by shaded cells. The mesh setup also means that light bounced onto the solar panels by reflective films can hit unevenly and still boost the panels' performance. Finally, onboard electronics maximize the cells' output.

MAXIMILIAN BODE ; COURTESY OF HANWHA SOLAR

Upfront



An elaborate structure cools and shields the D-Wave processor so that it can (apparently) conduct quantum calculations.

COURTESY OF D-WAVE

The CIA and Jeff Bezos Bet on Quantum Computing

With funding from the Amazon founder and the CIA's investment arm, the Canadian company D-Wave is gaining momentum for its new approach to computing.

By Tom Simonite

Inside a blocky building in a Vancouver suburb, across the street from a dowdy McDonald's, is a place chilled colder than anywhere else in the known universe. Inside that is a computer processor that Amazon founder Jeff Bezos and the CIA's investment arm, In-Q-Tel, believe can tap the quirks of quantum mechanics to unleash more computing power than any conventional computer chip. Bezos and In-Q-Tel are in a group of investors who just bet $30 million on this prospect.

If the bet works out, some of the world's thorniest computing problems, such as the hunt for new drugs or efforts to build artificial intelligence, could become less challenging. This development would also clear the tainted reputation of D-Wave Systems, the startup that has been pursuing a quantum computer for eight years.

D-Wave's supercooled processor is designed to master what software engineers call "optimization" problems—figuring out the most efficient delivery route, for example, or determining how the atoms in a protein will move around when it meets a drug compound. "Virtually everything has to do with optimization, and it's the bedrock of machine learning, which underlies virtually all the wealth creation on the Internet," says Geordie Rose, D-Wave's founder and chief technology officer.

Rose, a confident Canadian with a guitar and samurai sword propped in the corner of his windowless office, has been making grand claims since 2007, when he unveiled D-Wave's first proof-of-concept processor at the Computer History Museum in Mountain View, California. Attendees saw a D-Wave processor (apparently) solve sudoku puzzles and find a close match for a particular drug molecule in a collection of other compounds. But skepticism and accusations of fraud rained down on the company from academic experts on quantum computing. Rose's predictions about how quickly the company would increase the capabilities of its chips failed to come to fruition, and the company kept quiet.

Recently, however, the company has shown signs that it is finally ready to answer its critics. In May 2011, it published a paper in *Nature* that critical aca-

demics said proved for the first time that D-Wave's chips have some of the quantum properties needed to back up Rose's claims. Artificial-intelligence researchers at Google log into a D-Wave computer over the Internet to try it out, and 2011 also saw the company sign its first customer. Defense contractor Lockheed Martin paid $10 million for a computer for research into automatically detecting software bugs in complex projects such as the delayed F-35 fighter. Questions remain about just how its technology works, but D-Wave says more evidence is forthcoming. It is readying an improved processor that Rose says is the company's first true product rather than a piece of research equipment.

In D-Wave's headquarters is a bright white lab space dominated by four black monoliths—D-Wave's computers. Around 10 feet tall, they emit a rhythmic, high-pitched sound as supercooled gases circulate inside. Each of the machines has a door on the side and is mostly empty, with what looks like a ray gun descending from the ceiling—a widely spaced stack of five metal discs held together with cables, struts, and pipes plated with gold and copper. It is actually a cold gun: the structure is a chilly −269 °C (4 K) at the wide end and a few thousandths of a degree above absolute zero at its tip, where D-Wave's fingertip-sized chip can be found.

Whether the chip exploits quantum effects remains unclear. Even so, Google and Lockheed use it.

The processor in every computer you've used is made from silicon and patterned with transistors that create logic gates—switches that are either on (represented by a *1* in the computer's programming) or off (a *0*). D-Wave's processors are also made up of elements that switch between *1* and *0*, but these are loops of niobium alloy that become superconductors at very low temperatures. These loops—there are 512 of them in the newest processor—are known as qubits and can trap electrical current, which circles inside the loops either clockwise (signified by a *0*) or counterclockwise (*1*). Smaller superconducting loops called couplers link the qubits so they can interact and even influence one another to flip between *1* and *0*.

This delicate setup is designed so that the layout of qubits conforms to an algorithm that solves a particular kind of optimization problem at the core of many tasks difficult to solve on a conventional processor. Performing a calculation on D-Wave's chip requires providing the numbers to be fed into its hard-coded algorithm. After a wait of less than a second, the qubits settle into new values that represent a lower state of energy for the processor, revealing a potential solution to the original problem.

What happens during that crucial wait is a kind of quantum-mechanical argument. The qubits enter a quantum state where they are simultaneously *1* and *0*, like Schrödinger's cat being both dead and alive, and lock into a strange synchronicity known as entanglement. That allows the system of qubits to explore every possible final configuration in an instant before settling into the one that is simplest, or one very close to it.

At least, that's what D-Wave's scientists say. But Scott Aaronson, an MIT professor who studies quantum computation, says D-Wave's system could plausibly be solving problems without quantum effects, in which case it would simply be a very weird conventional computer. Aaronson says the company still needs to prove that its qubits really can become "entangled" and that the chip delivers a significant "quantum speed-up" compared with a classical computer working on the same problem. "In the past there was an enormous gap between the marketing claims and where the science was and that's come down, but there's still a gap," says Aaronson, who visited D-Wave's labs this year.

Rose counters that he is more focused on increasing his customers' computing power than on placating academic critics.

COURTESY OF KNOME

TO MARKET

Genomic Insights

knoSYS100

COMPANY:
Knome

PRICE:
$125,000 and up

AVAILABILITY:
Now

A computer that comes with genome analysis software could simplify the task that doctors and researchers face when trying to glean medically useful information from an individual's DNA. Sequencing costs have fallen precipitously in recent years; now interpreting the resulting data is the major challenge. Knome, based in Cambridge, Massachusetts, developed its hardware-and-software package to help labs spot genetic variations that may be linked to disease. Unlike rival products that are available or in development, Knome's system does not rely on remote servers in the cloud, which may reduce privacy concerns.

Why We Can't Solve Big Problems

By Jason Pontin

On July 21, 1969, Buzz Aldrin climbed gingerly out of Eagle, *Apollo 11*'s lunar module, and joined Neil Armstrong on the Sea of Tranquility. Looking up, he said, "Beautiful, beautiful, magnificent desolation." They were alone; but their presence on the moon's silent, gray surface was the culmination of a convulsive collective effort.

Eight years before, President John F. Kennedy had asked the United States Congress to "commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the Earth." His challenge disturbed the National Aeronautics and Space Administration's original plan for a stepped, multi-generational strategy: Wernher von Braun, NASA's chief of rocketry, had thought the agency would first send men into Earth's orbit, then build a space station, then fly to the moon, then build a lunar colony. A century hence, perhaps,

Buzz Aldrin on the moon, July 21, 1969. Reflected in his visor, the photographer: Neil Armstrong.

NASA

humans would travel to Mars. Kennedy's goal was also absurdly ambitious. A few weeks before his speech, NASA had strapped an astronaut into a tiny capsule atop a converted military rocket and shot him into space on a ballistic trajectory, as if he were a circus clown; but no American had orbited the planet. The agency didn't really know if what the president asked could be done in the time he allowed, but it accepted the call.

This required the greatest peacetime mobilization in the nation's history. Although NASA was and remains a civilian agency, the Apollo program was possible only because it was a lavishly funded, semi-militarized project: all the astronauts (with one exception) had been Air Force pilots and naval aviators; many of the agency's middle-aged administrators had served in the Second World War in some capacity; and the director of the program itself, Samuel Philips, was an Air Force general officer, drafted into service because of his effective management of the Minuteman missile program. In all, NASA spent $24 billion, or about $180 billion in today's dollars, on Apollo; at its peak in the mid-1960s, the agency enjoyed more than 4 percent of the federal budget. The program employed around 400,000 people and demanded the collaboration of about 20,000 companies, universities, and government agencies.

If Apollo commanded a significant portion of the treasure of the world's richest nation and the coöperation of all its estates, that was because Kennedy's challenge required NASA to solve a bewildering number of smaller problems decades ahead of technology's evolutionary schedule. The agency's solutions were often inelegant. To escape from orbit, NASA constructed 13 giant, single-use multistage rockets, capable of lifting 50 tons of payload and generating 7.6 million pounds of thrust. Only an ungainly modular spacecraft could be flown by the deadline; but docking the command and lunar modules midflight, sending the lunar module to the moon's surface, and then reuniting the modules in lunar orbit demanded a kind of spastic space dance and forced the agency's engineers to develop and test a long series of astronautical innovations. Men died, including the crew of *Apollo 1*, who burned in the cabin of their command module. But before the program ended in 1972, 24 men flew to the moon. Twelve walked on its surface, of whom Aldrin, following the death of Armstrong last August, is now the most senior.

Why did they go? They brought back little—841 pounds of old rocks, Aldrin's smuggled aesthetic bliss, and something most of the 24 emphasized: a new sense of the smallness and fragility of our home. (Jim Lovell, not untypically, remembered, "Everything that I ever knew—my life, my loved ones, the Navy—everything, the whole world, was behind my thumb.") The cynical, mostly correct answer is that Kennedy wanted to demonstrate the superiority of American rocketry over Soviet engineering: the president's challenge was made in May of 1961, little more than a month after Yuri Gagarin became the first human in space. But it does not adequately explain why the United States made the great effort it did, nor does it convey how the lunar landings were understood at the time.

Kennedy's words, spoken at Rice University in 1962, provide a better clue:

> But why, some say, the moon? Why choose this as our goal? … Why climb the highest mountain? Why, 35 years ago, fly the Atlantic? … We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our energies and skills …

Apollo was not seen only as a victory for one of two antagonistic ideologies. Rather, the strongest emotion at the time of the moon landings was of wonder at the transcendent power of technology. From his perch in Lausanne, Switzerland, the writer Vladimir Nabokov cabled the *New York Times,* "Treading the soil of the moon, palpating its pebbles, tasting the panic and splendor of the event, feeling in the pit of one's stomach the separation from terra—these form the most romantic sensation an explorer has ever known."

To contemporaries, the Apollo program occurred in the context of a long series of technological triumphs. The first half of the century produced the assembly line and the airplane, penicillin and a vaccine for tuberculosis; in the middle years of the century, polio was on its way to being eradicated; and by 1979 smallpox would be eliminated. More, the progress seemed to possess what Alvin Toffler dubbed an "accelerative thrust" in *Future Shock*, published in 1970. The adjectival swagger is pardonable: for decades, technology had been increasing the maximum speed of human travel. During most of history, we could go no faster than a horse or a boat with a sail; by the First World War, automobiles and trains could propel us at more than 100 miles an hour. Every decade thereafter, cars and planes sped humans faster. By 1961, a rocket-powered X-15 had been piloted to more than 4,000 miles per hour; in 1969, the crew of *Apollo 10* flew at 25,000. Wasn't it the very time to explore the galaxy—"to blow this great blue, white, green planet or to be blown from it," as Saul Bellow wrote in *Mr. Sammler's Planet* (also 1970)?

Since *Apollo 17*'s flight in 1972, no humans have been back to the moon, or gone anywhere beyond low Earth orbit. No one has traveled faster than the crew of *Apollo 10*. (Since the last flight of the supersonic *Concorde* in 2003, civilian travel has become *slower*.) Blithe optimism about technology's powers has evaporated, too, as big problems that people had imagined technology would solve, such as hunger, poverty, malaria, climate change,

Perhaps the most famous photograph from the Apollo lunar landings: Buzz Aldrin's footprint in the moon's gray, powdery surface.

NASA

cancer, and the diseases of old age, have come to seem intractably hard.

I remember sitting in the living room in Berkeley, California, watching the liftoff of *Apollo 17*. I was five; my mother admonished me not to stare at the fiery exhaust of the Saturn 5 rocket. I vaguely knew that this was the last of the moon missions—but I was absolutely certain that there would be Mars colonies in my lifetime. What happened?

Parochial Explanations

That *something* happened to humanity's capacity to solve big problems is a commonplace. Recently, however, the complaint has developed a new stridency among Silicon Valley's investors and entrepreneurs, although it is usually expressed a little differently: people say there is a paucity of real innovations. Instead, they worry, technologists have diverted us and enriched themselves with trivial toys.

The motto of Founders Fund, a venture capital firm started by Peter Thiel, a cofounder of PayPal, is "We wanted flying cars—instead we got 140 characters." Founders Fund matters, because it is the investment arm of what is known locally as the "PayPal Mafia," currently the dominant faction in Silicon Valley, which remains the most important area on the planet for technological innovation. (Other members include Elon Musk, the founder of SpaceX and Tesla Motors; Reid Hoffman, executive chairman of LinkedIn; and Keith Rabois, chief operating officer of the mobile payments company Square.) Thiel is caustic: last year he told the *New Yorker* that he didn't consider the iPhone a technological breakthrough. "Compare [it] with the Apollo program," he said. The Internet is "a net plus—but not a big one." Twitter gives 500 people "job security for the next decade," but "what value does it create for the entire economy?" And so on. Max Levchin, another cofounder of PayPal, says, "I feel like we should be aiming higher. The founders of a number of startups I encounter have no real intent of getting anywhere huge ... There's an awful lot of effort being expended that is just never going to result in meaningful, disruptive innovation."

But Silicon Valley's explanation of *why* there are no disruptive innovations is parochial and reductive: the markets—in particular, the incentives that venture capital provides entrepreneurs—are to blame. According to Founders Fund's manifesto, "What Happened to the Future?," written by Bruce Gibney, a partner at the firm: "In the late 1990s, venture portfolios began to reflect a different sort of future ... Venture investing shifted away from funding transformational companies and toward companies that solved incremental problems or even fake problems ... VC has ceased to be the funder of the future, and instead become a funder of features, widgets, irrelevances." Computers and communications technologies advanced because they were well and properly funded, Gibney argues. But what seemed futuristic at the time of *Apollo 11* "remains futuristic, in part because these technologies never received the sustained funding lavished on the electronics industries."

The argument, of course, is wildly hypocritical. PayPal's capos made their fortunes in public stock offerings and acquisitions of companies that did more or less trivial things. Levchin's last startup, Slide, was a Founders Fund investment: it was acquired by Google in 2010 for about $200 million and shuttered earlier this year. It developed Facebook widgets such as SuperPoke and FunWall.

But the real difficulty with Silicon Valley's explanation is that it is insufficient to the case. The argument that venture capitalists lost their appetite for risky but potentially important technologies clarifies what's wrong with venture capital and tells us why half of all funds have provided flat or negative returns for the last decade. It also usefully explains how a collapse in nerve reduced the scope of the companies that got funded: with the exception of Google (which wants to "organize the world's information and make it universally accessible and useful"), the ambitions of startups founded in the last 15 years do seem derisory compared with those of companies like Intel, Apple, and Microsoft, founded from the 1960s to the late 1970s. (Bill Gates, Microsoft's founder, promised to "put a computer in every home and on every desktop," and Apple's Steve Jobs said he wanted to make the "best computers in the world.") But the Valley's explanation conflates all of technology with the technologies that venture capitalists like: traditionally, as Gibney concedes, digital technologies. Even during the years when VCs were most risk-happy, they preferred investments that required little capital and offered an exit within eight to 10 years. The venture capital business has always struggled to invest profit-

ably in technologies, such as biotechnology and energy, whose capital requirements are large and whose development is uncertain and lengthy; and VCs have *never* funded the development of technologies that are meant to solve big problems and possess no obvious, immediate economic value. The account is a partial explanation that forces us to ask: putting aside the personal-computer revolution, if we once did big things but do so no longer, then what changed?

Silicon Valley's explanation has this fault, too: it doesn't tell us what should be done to encourage technologists to solve big problems, beyond asking venture capitalists to make better investments. (Founders Fund promises to "run the experiment" and "invest in smart people solving difficult problems, often difficult scientific or engineering problems.") Levchin, Thiel, and Garry Kasparov, the former world chess champion, had planned a book, to be titled *The Blueprint*, that would "explain where the world's innovation has gone." Originally intended to be released in March of this year, it has been indefinitely postponed, according to Levchin, because the authors could not agree on a set of prescriptions.

Let's stipulate that venture-backed entrepreneurialism is essential to the development and commercialization of technological innovations. But it is not sufficient by itself to solve big problems, nor could its relative sickliness by itself undo our capacity for collective action through technology.

Irreducible Complexities

The answer is that these things are complex, and that there is no one simple explanation.

Sometimes we choose not to solve big technological problems. We could travel to Mars if we wished. NASA has the outline of a plan—or, in its bureaucratic jargon, a "design reference architecture." To a surprising degree, the agency knows how it might send humans to Mars and bring them home. "We know what the challenges are," says Bret Drake, the deputy chief architect for NASA's human spaceflight architecture team. "We know what technologies, what systems we need" (see "The Deferred Dreams of Mars," p. 66). As Drake explains, the mission would last about two years; the astronauts would spend 12 months in transit and 500 days on the surface, studying the geology of the planet and trying to understand whether it ever harbored life. Needless to say, there's much that NASA doesn't know: whether it could adequately protect the crew from cosmic rays, or how to land them safely, feed them, and house them. But if the agency received more money or reallocated its current spending and began working to solve those problems now, humans could walk on the Red Planet sometime in the 2030s.

We won't, because there are, everyone feels, more useful things to do on Earth. Going to Mars, like going to the moon, would follow upon a political decision that inspired or was inspired by public support. But almost no one feels Buzz Aldrin's "imperative to explore" (see the astronaut's sidebar on p. 70).

Sometimes we fail to solve big problems because our institutions have failed. In 2010, less than 2 percent of the world's energy consumption was derived from advanced renewable sources such as wind, solar, and biofuels. (The most common renewable sources of energy are still hydroelectric power and the burning of biomass, which means wood and cow dung.) The reason is economic: coal and natural gas are cheaper than solar and wind, and petroleum is cheaper than biofuels. Because climate change is a real and urgent problem, and because the main cause of global warming is carbon dioxide released as a by-product of burning fossil fuels, we need renewable energy technologies that can compete on price with coal, natural gas, and petroleum. At the moment, they don't exist.

Happily, economists, technologists, and business leaders agree on what national policies and international treaties would spur the development and broad use of such alternatives. There should be a significant increase in public investment for energy research and development, which has fallen in the United States from a height of 10 percent in 1979 to 2 percent of total R&D spending, or just $5 billion a year. (Two years ago, Bill Gates, Xerox chief executive Ursula Burns, GE chief executive Jeff Immelt, and John Doerr, the Silicon Valley venture capitalist, called for a threefold increase in public investments in energy research.) There should be some kind of price on carbon, now a negative externality, whether it is a transparent tax or some more opaque market mechanism. There should be a regulatory framework that treats carbon dioxide emissions as pollution, setting upper limits on how much pollution companies and nations can release. Finally, and least concretely, energy experts agree that even if there were more investment in research, a price on carbon, and some kind of regulatory framework, we would *still* lack one vital thing: sufficient facilities to demonstrate and test new energy technologies. Such facilities are typically too expensive for private companies to build. But without a practical way to collectively test and optimize innovative energy technologies, and without some means to share the risks of development, alternative energy sources will continue to have little impact on energy use, given that any new technology will be more expensive at first than fossil fuels.

Less happily, there is no hope of any U.S. energy policy or international treaties that reflect this intellectual consensus, because one political party in the United States is reflexively opposed to industrial regulations and affects to doubt that

human beings are causing climate change, and because the emerging markets of China and India will not reduce their emissions without offset benefits that the industrialized nations cannot provide. Without international treaties or U.S. policy, there will probably be no competitive alternative sources of energy in the near future, barring what is sometimes called an "energy miracle."

Sometimes big problems that had seemed technological turn out not to be so, or could more plausibly be solved through other means. Until recently, famines were understood to be caused by failures in food supply (and therefore seemed addressable by increasing the size and reliability of the supply, potentially through new agricultural or industrial technologies). But Amartya Sen, a Nobel laureate economist, has shown that famines are political crises that catastrophically affect food distribution. (Sen was influenced by his own experiences. As a child he witnessed the Bengali famine of 1943: three million displaced farmers and poor urban dwellers died unnecessarily when wartime hoarding, price gouging, and the colonial government's price-controlled acquisitions for the British army made food too expensive. Sen demonstrated that food production was actually *higher* in the famine years.) Technology can improve crop yields or systems for storing and transporting food; better responses by nations and nongovernmental organizations to emerging famines have reduced their number and severity. But famines will still occur because there will always be bad governments.

Yet the hope that an entrenched problem with social costs should have a technological solution is very seductive—so much so that disappointment with technology is inevitable. Malaria, which the World Health Organization estimates affected 216 million people in 2010, mostly in the poor world, has resisted technological solutions: infectious mosquitoes are everywhere in the tropics, treatments are expensive, and the poor are a terrible market for drugs. The most efficient solutions to the problem of malaria turn out to be simple: eliminating standing water, draining swamps, providing mosquito nets, and, most of all, increasing prosperity. Combined, they have reduced malarial infections. But that hasn't stopped technologists such as Bill Gates and Nathan Myhrvold, the former chief technology officer of Microsoft (who writes about the role of private investors in spurring innovation on p. 80), from funding research into recombinant vaccines, genetically modified mosquitoes, and even mosquito-zapping lasers. Such ideas can be ingenious, but they all suffer from the vanity of trying to impose a technological solution on what is a problem of poverty.

Finally, sometimes big problems elude any solution because we don't really understand the problem. The first successes of biotechnology in the late 1970s were straightforward: breakthroughs in manufacturing, in which recombinant *E. coli* bacteria were coaxed into producing synthetic versions of insulin or human growth hormone, proteins whose functions we thoroughly understood. Further breakthroughs in biomedicine have been more difficult to achieve, however, because we have struggled to understand the fundamental biology of many diseases. President Richard Nixon declared war on cancer in 1971; but we soon discovered there were many kinds of cancer, most of them fiendishly resistant to treatment, and it is only in the last decade, as we have begun to sequence the genomes of different cancers and to understand how their mutations express themselves in different patients, that effective, targeted therapies have come to seem viable. (To learn more, see "Cancer Genomics" on p. 59.) Or consider the "dementia plague," as Stephen S. Hall does on p. 50. As the populations of the industrialized nations age, it is emerging as the world's most pressing health problem: by 2050, palliative care in the United States alone will cost $1 trillion a year. Yet we understand almost nothing about dementia and have no effective treatments. Hard problems are hard.

What to Do

It's not true that we can't solve big problems through technology; we can. We must. But all these elements must be present: political leaders and the public must care to solve a problem, our institutions must support its solution, it must really be a technological problem, and we must understand it.

The Apollo program, which has become a metaphor for technology's capacity to solve big problems, met these criteria, but it is an irreproducible model for the future. This is not 1961: there is no galvanizing historical context akin to the Cold War, no likely politician who can heroize the difficult and dangerous, no body of engineers who yearn for the productive regimentation they had enjoyed in the military, and no popular faith in a science-fictional mythology such as exploring the solar system. Most of all, going to the moon was easy. It was only three days away. Arguably, it wasn't even solving much of a problem. We are left alone with our day, and the solutions of the future will be harder won.

We don't lack for challenges. A billion people want electricity, millions are without clean water, the climate is changing, manufacturing is inefficient, traffic snarls cities, education is a luxury, and dementia or cancer will strike almost all of us if we live long enough. In this special issue of *MIT Technology Review*, we examine these problems and introduce you to the indefatigable technologists who refuse to give up trying to solve them. T

Jason Pontin is editor in chief of MIT Technology Review.

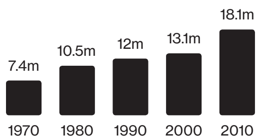
The Crisis in
Higher Education

Online versions of college courses are attracting hundreds of thousands of students, millions of dollars in funding, and accolades from university administrators. Is this a fad, or is higher education about to get the overhaul it needs?

By Nicholas Carr

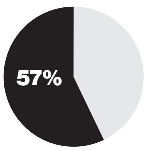
Illustrations by Brian Cronin

Undergraduate enrollment in the United States



Average cost of a year on campus **$27,435**

Percentage of people who say the value is fair or poor



DATA FROM INSTITUTE OF EDUCATION SCIENCES AND PEW RESEARCH CENTER

A hundred years ago, higher education seemed on the verge of a technological revolution. The spread of a powerful new communication network—the modern postal system—had made it possible for universities to distribute their lessons beyond the bounds of their campuses. Anyone with a mailbox could enroll in a class. Frederick Jackson Turner, the famed University of Wisconsin historian, wrote that the "machinery" of distance learning would carry "irrigating streams of education into the arid regions" of the country. Sensing a historic opportunity to reach new students and garner new revenues, schools rushed to set up correspondence divisions. By the 1920s, postal courses had become a full-blown mania. Four times as many people were taking them as were enrolled in all the nation's colleges and universities combined.

The hopes for this early form of distance learning went well beyond broader access. Many educators believed that correspondence courses would be better than traditional on-campus instruction because assignments and assessments could be tailored specifically to each student. The University of Chicago's Home-Study Department, one of the nation's largest, told prospective enrollees that they would "receive individual personal attention," delivered "according to any personal schedule and in any place where postal service is available." The department's director claimed that correspondence study offered students

an intimate "tutorial relationship" that "takes into account individual differences in learning." The education, he said, would prove superior to that delivered in "the crowded classroom of the ordinary American University."

We've been hearing strikingly similar claims today. Another powerful communication network—the Internet—is again raising hopes of a revolution in higher education. This fall, many of the country's leading universities, including MIT, Harvard, Stanford, and Princeton, are offering free classes over the Net, and more than a million people around the world have signed up to take them. These "massive open online courses," or MOOCs, are earning praise for bringing outstanding college teaching to multitudes of students who otherwise wouldn't have access to it, including those in remote places and those in the middle of their careers. The online classes are also being promoted as a way to bolster the quality and productivity of teaching in general—for students on campus as well as off. Former U.S. secretary of education William Bennett has written that he senses "an Athens-like renaissance" in the making. Stanford president John Hennessy told the *New Yorker* he sees "a tsunami coming."

The excitement over MOOCs comes at a time of growing dissatisfaction with the state of college education. The average price tag for a bachelor's degree has shot up to more than $100,000. Spending four years on campus often leaves young people or their parents weighed down with big debts, a burden not only on their personal finances but on the overall economy. And many people worry that even as the cost of higher education has risen, its quality has fallen. Dropout rates are often high, particularly at public colleges, and many graduates display little evidence that college improved their critical-thinking skills. Close to 60 percent of Americans believe that the country's colleges and universities are failing to provide students with "good value for the money they and their families spend," according to a 2011 survey by the Pew Research Center. Proponents of MOOCs say the efficiency and flexibility of online instruction will offer a timely remedy.

But not everyone is enthusiastic. The online classes, some educators fear, will at best prove a distraction to college administrators; at worst, they will end up diminishing the quality of on-campus education. Critics point to the earlier correspondence-course mania as a cautionary tale. Even as universities rushed to expand their home-study programs in the 1920s, investigations revealed that the quality of the instruction fell short of the levels promised and that only a tiny fraction of enrollees actually completed the courses. In a lecture at Oxford in 1928, the eminent American educator Abraham Flexner delivered a withering indictment of correspondence study, claiming that it promoted "participation" at the expense of educational rigor. By the 1930s, once-eager faculty and administrators had lost interest in teaching by mail. The craze fizzled.

Is it different this time? Has technology at last advanced to the point where the revolutionary promise of distance learning can be fulfilled? We don't yet know; the fervor surrounding MOOCs makes it easy to forget that they're still in their infancy. But even at this early juncture, the strengths and weaknesses of this radically new form of education are coming into focus.

WHY IT MATTERS

Many people, especially those in remote places, could improve their lot in life by gaining access to top-notch university courses.

Rise of the MOOCs

"I had no clue what I was doing," Sebastian Thrun says with a chuckle, as he recalls his decision last year to offer Stanford's Introduction to Artificial Intelligence course free online. The 45-year-old robotics expert had a hunch that the class, which typically enrolls a couple of hundred undergraduates, would prove a draw on the Net. After all, he and his co-professor, Peter Norvig, were both Silicon Valley stars, holding top research posts at Google in addition to teaching at Stanford. But while Thrun imagined that enrollment might reach 10,000 students, the actual number turned out to be more than an order of magnitude higher. When the class began, in October 2011, some 160,000 people had signed up.

The experience changed Thrun's life. Declaring "I can't teach at Stanford again," he announced in January that he was joining two other roboticists to launch an ambitious educational startup called Udacity. The venture, which bills itself as a "21st-century university," is paying professors from such schools as Rutgers and the University of Virginia to give open courses on the Net, using the technology originally developed for the AI class. Most of the 14 classes Udacity offers fall into the domains of computer science and mathematics, and Thrun says it will concentrate on such fields for now. But his ambitions are hardly narrow: he sees the traditional university degree as an outdated artifact and believes Udacity will provide a new form of lifelong education better suited to the modern labor market.

Udacity is just one of several companies looking to capitalize on the burgeoning enthusiasm for MOOCs. In April, two of Thrun's colleagues in Stanford's computer science department, Daphne Koller and Andrew Ng, rolled out a similar startup called Coursera. Like Udacity,

Coursera is a for-profit business backed with millions of dollars in venture capital. Unlike Udacity, Coursera is working in concert with big universities. Where Thrun wants to develop an alternative to a traditional university, Koller and Ng are looking to build a system that established schools can use to deliver their own classes over the Net. Coursera's original partners included not only Stanford but Princeton, Penn, and the University of Michigan, and this summer the company announced affiliations with 29 more schools. It already has about 200 classes on offer, in fields ranging from statistics to sociology.

On the other side of the country, MIT and Harvard joined forces in May to form edX, a nonprofit that is also offering tuition-free online classes to all comers. Bankrolled with $30 million from each school, edX is using an open-source teaching platform developed at MIT. It includes video lessons and discussion forums similar to those offered by its for-profit rivals, but it also incorporates virtual laboratories where students can carry out simulated experiments. This past summer, the University of California at Berkeley joined edX, and in September the program debuted its first seven classes, mainly in math and engineering. Overseeing the launch of edX is Anant Agarwal, the former director of MIT's Computer Science and Artificial Intelligence Laboratory.

The leaders of Udacity, Coursera, and edX have not limited their aspirations to enhancing distance learning. They believe that online instruction will become a cornerstone of the college experience for on-campus students as well. The merging of virtual classrooms with real classrooms, they say, will propel academia forward. "We are reinventing education," declares Agarwal. "This will change the world."

Professor Robot

Online courses aren't new; big commercial outfits like the University of Phoenix and DeVry University offer thousands of them, and many public colleges allow students to take classes on the Net for credit. So what makes MOOCs different? As Thrun sees it, the secret lies in "student engagement." Up to now, most Internet classes have consisted largely of videotaped lectures, a format that

e-institutions

A look at some of the major online education efforts

Name	Founded	Enrollees	Model	Details
Coursera	2012	1.5 million	for profit	Backed by $22 million from VCs and colleges. Nearly 200 courses available, over a wide range of subjects.
edX	2012	155,000*	nonprofit	MIT and Harvard have each pledged $30 million. Seven courses available. Will offer certificates to people who complete the work.
Udacity	2012	739,000	for profit	Got $5 million in seed funding. Offers 14 courses, focused on computer science, ranging from beginner to intermediate to advanced.
Open Learning Initiative	2002	51,000	nonprofit	Carnegie Mellon project offers Web classes and researches online teaching methods. Has 15 courses, including sciences and French.
University of Phoenix	1976	346,000	for profit	Has physical campuses for undergrads and grad students but also offers individual courses online.
The Open University	1969	264,000	nonprofit	Based in the U.K. Combines Web curriculum with physical study centers. Offers hundreds of free online courses in a range of fields.

**EdX figure is for Spring 2012 class only.*

Thrun sees as deeply flawed. Classroom lectures are in general "boring," he says, and taped lectures are even less engaging: "You get the worst part without getting the best part." While MOOCs include videos of professors explaining concepts and scribbling on whiteboards, the talks are typically broken up into brief segments, punctuated by on-screen exercises and quizzes. Peppering students with questions keeps them involved with the lesson, Thrun argues, while providing the kind of reinforcement that has been shown to strengthen comprehension and retention.

Norvig, who earlier this year taught a Udacity class on computer programming, points to another difference between MOOCs and their predecessors. The economics of online education, he says, have improved dramatically. Cloud computing facilities allow vast amounts of data to be stored and transmitted at very low cost. Lessons and quizzes can be streamed free over YouTube and other popular media delivery services. And social networks like Facebook provide models for digital campuses where students can form study groups and answer each other's questions. In just the last few years, the cost of delivering interactive multimedia classes online has dropped precipitously. That's made it possible to teach huge numbers of students without charging them tuition.

It's hardly a coincidence that Udacity, Coursera, and edX are all led by computer scientists. To fulfill their grand promise—making college at once cheaper and better—MOOCs will need to exploit the latest breakthroughs in large-scale data processing and machine learning, which enable computers to adjust to the tasks at hand. Delivering a complex class to thousands of people simultaneously demands a high degree of automation. Many of the labor-intensive tasks traditionally performed by professors and teaching assistants—grading tests, tutoring, moderating discussions—have to be done by computers. Advanced analytical software is also required to parse the enormous amounts of information about student behavior collected during the classes. By using algorithms to spot patterns in the data, programmers hope to gain insights into learning styles and teaching strategies, which can then be used to refine the technology further. Such artificial-intelligence techniques will, the MOOC pioneers believe, bring higher education out of the industrial era and into the digital age.

To fulfill their grand promise, MOOCs will need to exploit the latest breakthroughs in data processing and machine learning. Delivering a complex class to thousands of people simultaneously demands a high degree of automation.

While their ambitions are vast, Thrun, Koller, and Agarwal all stress that their fledgling organizations are just starting to amass information from their courses and analyze it. "We haven't yet used the data in a systematic way," says Thrun. It will be some time before the companies are able to turn the information they're collecting into valuable new features for professors and students.

To see the cutting edge in computerized teaching today, you have to look elsewhere—in particular, to a small group of academic testing and tutoring outfits that are hard at work translating pedagogical theories into software code.

One of the foremost thinkers in this field is a soft-spoken New Yorker named David Kuntz. In 1994, after earning his master's degree in philosophy and working as an epistemologist, or knowledge theorist, for the Law School Admission Council (the organization that administers the LSAT examinations), Kuntz joined the Educational Testing Service, which runs the SAT college-admission tests. ETS was eager to use the burgeoning power of computers to design more precise exams and grade them more efficiently. It set Kuntz and other philosophers to work on a very big question: how do you use software to measure meaning, promote learning, and evaluate understanding? The question became even more pressing when the World Wide Web opened the Internet to the masses. Interest in "e-learning" surged, and the effort to develop sophisticated teaching and testing software combined with the effort to design compelling educational websites.

Three years ago, Kuntz joined a small Manhattan startup called Knewton as its head of research. The company specializes in the budding discipline of adaptive learning. Like other trailblazers in instructional software, including the University of California, Irvine, spinoff ALEKS, Carnegie Mellon's Open Learning Initiative, and the much celebrated Khan Academy, it is developing online tutoring systems that can adapt to the needs and learning styles of individual students as they proceed through a course of instruction. Such programs, says Kuntz, "get better as more data is collected." Software for, say, teaching algebra can be written to reflect alternative theories of learning, and then, as many

Another Way to Think about Learning

By Nicholas Negroponte

Children in Ethiopia are teaching themselves to use tablet computers in a project that aims to test the promise of self-instruction.

I believe that we get into trouble when knowing becomes a surrogate for learning. The meteoric rise of modern instructionism, including the misguided belief that there is a perfect way to teach something, is alarming because of the unlimited support it is getting from Bill Gates, Google, and my own institution, MIT.

I have advocated an approach to teaching that distinguishes "learning" from "being instructed." One Laptop per Child (OLPC), a nonprofit association that I founded, launched the so-called XO Laptop in 2005 to help children teach themselves how to, among other things, program the computer itself. There are 2.5 million XOs in the hands of kids today in 40 countries, with 25 languages in use. In Uruguay, where all 400,000 kids have an XO laptop, knowing how to program is required in schools. The same is now true in Estonia. In Ethiopia, 5,000 kids are writing computer programs in the language Squeak.

OLPC represents about $1 billion in sales worldwide since 2005—it's bigger than most people think. What have we learned? That kids learn a great deal by themselves. The question is, how much?

To explore this question, we have now turned our attention to the 100 million kids worldwide who do not go to first grade. Most of them do not go because there is no school, there are no literate adults in their village, and there is little promise of that changing soon. My colleagues and I have started an experiment in two such villages, asking a simple question: Can children learn how to read on their own?

In an effort to find out, we have delivered fully loaded Motorola Xoom tablets to two villages in Ethiopia, one per child, with no instruction or instructional material whatsoever. The tablets come with a solar panel, because there is no electricity in these villages. They contain modestly curated games, books, cartoons, movies—just to see what the kids will play with and whether they can figure out how to use them. We then monitor each tablet remotely, in this case by swapping SIM cards weekly (through a process affectionately known as sneakernet).

Within minutes of arrival, the tablets were unboxed and turned on by the kids themselves. After the first week, on average, 47 apps were used per day. After week two, the kids were playing games to race each other in saying the ABCs.

Will this lead to deep reading? The votes are still out. But if a child can learn to read, he or she can read to learn. If these kids were reading at, say, a third-grade level in 18 months, that would be transformational.

Whether this can happen has yet to be proved. But not only will the results tell us how to reach the rest of the 100 million kids much faster than we can by building schools and training teachers, they should also tell us a great deal about learning in the developed world. If kids in Ethiopia learn to read without school, what does that say about kids in New York City who do not learn even with school?

The message will be very simple: children can learn a great deal by themselves. More than we give them credit for. Curiosity is natural, and all kids have it unless it is whipped out of them, often by school. Making things, discovering things, and sharing things are keys. Having massive libraries of explicative material like modern-day encyclopedias or textbooks is fine. But such access may be much less significant than building a world in which ideas are shaped, discovered, and reinvented in the name of learning by doing and discovery.

Nicholas Negroponte, founder and chairman emeritus of MIT's Media Lab, is the chairman of the One Laptop Per Child Foundation.

MATT KELLER

students proceed through the program, the theories can be tested and refined and the software improved. The bigger the data sets, the more adept the systems become at providing each student with the right information in the right form at the right moment.

Knewton has introduced a remedial math course for incoming college students, and its technology is being incorporated into tutoring programs offered by the textbook giant Pearson. But Kuntz believes that we're only just beginning to see the potential of educational software. Through the intensive use of data analysis and machine learning techniques, he predicts, the programs will advance through several "tiers of adaptivity," each offering greater personalization through more advanced automation.

In the initial tier, which is already largely in place, the sequence of steps a student takes through a course depends on that student's choices and responses. Answers to a set of questions may, for example, trigger further instruction in a concept that has yet to be mastered—or propel the student forward by introducing material on a new topic. "Each student," explains Kuntz, "takes a different path."

In the next tier, which Knewton plans to reach soon, the mode in which material is presented adapts automatically to each student. Although the link between media and learning remains controversial, many educators believe that different students learn in different ways. Some learn best by reading text, others by watching a demonstration, others by playing a game, and still others by engaging in a dialogue. A student's ideal mode may change, moreover, at each stage in a course—or even at different times during the day. A video lecture may be best for one lesson, while a written exercise may be best for the next. By monitoring how students interact with the teaching system itself—when they speed up, when

they slow down, where they click—a computer can learn to anticipate their needs and deliver material in whatever medium promises to maximize their comprehension and retention.

Looking toward the future, Kuntz says that computers will ultimately be able to tailor an entire "learning environment" to fit each student. Elements of the program's interface, for example, will change as the computer senses the student's optimum style of learning.

Big Data on Campus

The advances in tutoring programs promise to help many college, high-school, and even elementary students master basic concepts. One-on-one instruction has long been known to provide substantial educational benefits, but its high cost has constrained its use, particularly in public schools. It's likely that if computers are used in place of teachers, many more students will be able to enjoy the benefits of tutoring. According to one recent study of undergraduates taking statistics courses at public universities, the latest of the online tutoring systems seem to produce roughly the same results as face-to-face instruction.

While MOOCs are incorporating adaptive learning routines into their software, their ambitions for data mining go well beyond tutoring. Thrun says that we've only seen "the tip of the iceberg." What particularly excites him and other computer scientists about free online classes is that thanks to their unprecedented scale, they can generate the immense quantities of data required for effective machine learning. Koller says that Coursera has set up its system with intensive data collection and analysis in mind. Every variable in a course is tracked. When a student pauses a video or increases its playback speed, that choice is captured in the Coursera database. The same thing happens when a student answers a quiz question, revises an assignment, or comments in a forum. Every action, no matter how inconsequential it may seem, becomes grist for the statistical mill.

Assembling information on student behavior at such a minute level of detail, says Koller, "opens new avenues for understanding learning." Previously hidden patterns in the way students navigate and master complex subject matter can be brought to light.

The number-crunching also promises to benefit teachers and students directly, she adds. Professors will receive regular reports on what's working in their classes and what's not. And by pinpointing "the most predictive factors for success," MOOC software will eventually be able to guide each student onto "the right trajectory." Koller says she hopes that Lake Wobegon, the mythical town in which "all students are above average," will "come to life."

MIT and Harvard are designing edX to be as much a tool for educational research as a digital teaching platform, Anant Agarwal says. Scholars are already beginning to use data from the system to test hypotheses about how people learn, and as the portfolio of courses grows, the opportunities for research will proliferate. Beyond generating pedagogical insights, Agarwal foresees many other practical applications for the edX data bank. Machine learning may, for instance, pave the way for an automated system to detect cheating in online classes, a challenge that is becoming more pressing as universities consider granting certificates or even credits to students who complete MOOCs.

With a data explosion seemingly imminent, it's hard not to get caught up in the enthusiasm of the MOOC architects. Even though their work centers on computers, their goals are deeply humanistic. They're looking to use machine learning to foster student learning, to deploy artificial intelligence in the service of human intelligence. But the enthusiasm should be tempered by skepticism. The benefits of machine learning in education remain largely theoretical. And even if AI techniques generate genuine advances in pedagogy, those breakthroughs may have limited application. It's one thing for programmers to automate courses of instruction when a body of knowledge can be defined explicitly and a student's progress measured precisely. It's a very different thing to try to replicate on a computer screen the intricate and sometimes ineffable experiences of teaching and learning that take place on a college campus.

The promoters of MOOCs have a "fairly naïve perception of what the analysis of large data sets allows," says Timothy Burke, a history professor at Swarthmore College. He contends that distance educa-

Scholars who are skeptical of MOOCs warn that the essence of a college education lies in the subtle interplay between students and teachers that cannot be simulated by machines, no matter how sophisticated the programming.

tion has historically fallen short of expectations not for technical reasons but, rather, because of "deep philosophical problems" with the model. He grants that online education may provide efficient training in computer programming and other fields characterized by well-established procedures that can be codified in software. But he argues that the essence of a college education lies in the subtle interplay between students and teachers that cannot be simulated by machines, no matter how sophisticated the programming.

Alan Jacobs, a professor of English at Wheaton College in Illinois, raises similar concerns. In an e-mail to me, he observed that the work of college students "can be affected in dramatic ways by their reflection on the rhetorical situations they encounter in the classroom, in real-time synchronous encounters with other people." The full richness of such conversations can't be replicated in Internet forums, he argued, "unless the people writing online have a skilled novelist's ability to represent complex modes of thought and experience in prose." A computer screen will never be more than a shadow of a good college classroom. Like Burke, Jacobs worries that the view of education reflected in MOOCs has been skewed toward that of the computer scientists developing the platforms.

Flipping the Classroom

The designers and promoters of MOOCs don't suggest that computers will make classrooms obsolete. But they do argue that online instruction will change the nature of teaching on campus, making it more engaging and efficient. The traditional model of instruction, where students go to class to listen to lectures and then head off on their own to complete assignments, will be inverted. Students will listen to lectures and review other explanatory material alone on their computers (as some middle-school and high-school students already do with Khan Academy videos), and then they'll gather in classrooms to explore the subject matter more deeply—through discussions with professors, say, or through lab exercises. In theory, this "flipped classroom" will allocate teaching time more rationally, enriching the experience of both professor and student.

Here, too, there are doubts. One cause for concern is the high dropout rate that has plagued the early MOOCs. Of the 160,000 people who enrolled in Norvig and Thrun's AI class, only about 14 percent ended up completing it. Of the 155,000 students who signed up for an MIT course on electronic circuits earlier this year, only 23,000 bothered to finish the first problem set. About 7,000, or 5 percent, passed the course. Shepherding thousands of students through a college class is a remarkable achievement by any measure—typically only about 175 MIT students finish the circuits course each year—but the dropout rate highlights the difficulty of keeping online students attentive and motivated. Norvig acknowledges that the initial enrollees in MOOCs have been an especially self-motivated group. The real test, particularly for on-campus use of online instruction, will come when a broader and more typical cohort takes the classes. MOOCs will have to inspire a wide variety of students and retain their interest as they sit in front of their computers through weeks of study.

The greatest fear among the critics of MOOCs is that colleges will rush to incorporate online instruction into traditional classes without carefully evaluating the possible drawbacks. Last fall, shortly before he cofounded Coursera, Andrew Ng adapted his Stanford course on machine learning so that online students could participate, and thousands enrolled. But at least one on-campus student found the class wanting. Writing on his blog, computer science major Ben Rudolph complained that the "academic rigor" fell short of Stanford's standards. He felt that the computerized assignments, by providing automated, immediate hints and guidance, failed to encourage "critical thinking." He also reported a sense of isolation. He "met barely anyone in [the] class," he said, because "everything was done alone in my room." Ng has staunchly defended the format of the class, but the fact is that no one really knows how an increasing stress on computerized instruction will alter the dynamics of college life.

The leaders of the MOOC movement acknowledge the challenges they face. Perfecting the model, says Agarwal, will require "sophisticated inventions" in many areas, from grading essays to granting credentials. This will only get harder as the online courses expand further into the open-ended, exploratory realms of the liberal arts, where knowledge is rarely easy to codify and the success of a class can hinge on a professor's ability to guide students toward unexpected insights. The outcome of this year's crop of MOOCs should tell us a lot more about the value of the classes and the role they'll ultimately play in the educational system.

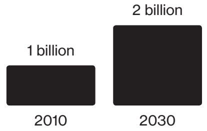
At least as daunting as the technical challenges will be the existential questions that online instruction raises for universities. Whether or not massive open courses live up to their hype, they will force college administrators and professors to reconsider many of their assumptions about the form and meaning of teaching. For better or worse, the Net's disruptive forces have arrived at the gates of academia.

Nicholas Carr is the author of The Shallows: What the Internet Is Doing to Our Brains. *His last article for* Technology Review *was "The Library of Utopia," which appeared in May/June 2012.*

SOLUTIONS • TRAFFIC

Self-Driving Cars

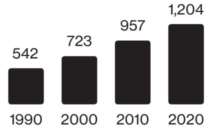
Cars on the world's roads, actual and projected



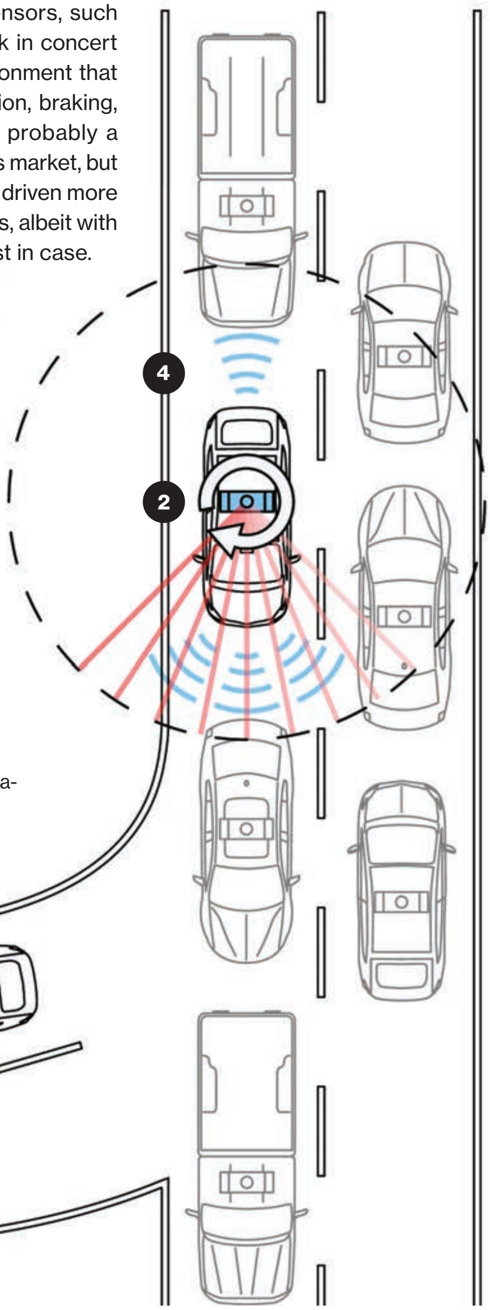
Traffic's 2010 cost in the United States, in lost productivity and wasted fuel

$101 billion

Actual and projected worldwide road deaths, in thousands

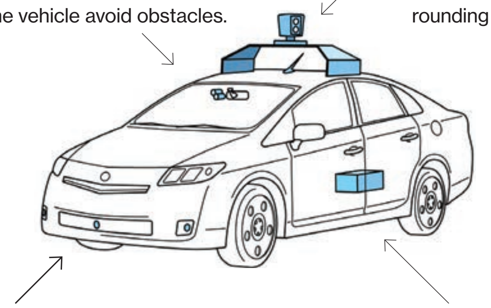


Cars that need no human drivers have the potential to increase productivity, unsnarl traffic, and sharply reduce accidents. Such cars could safely travel much closer together on the road, and people could work—or nap—while being whisked along. Two-way data feeds could help them learn the best travel routes while warning them of new obstacles and sending them instructions about how to queue at intersections. Onboard sensors, such as the ones shown here, would work in concert to create a clear picture of the environment that could inform autonomous acceleration, braking, and steering. Self-driving cars are probably a decade from being ready for the mass market, but they work: Google's prototypes have driven more than 300,000 miles without accidents, albeit with humans sitting in the driver's seat just in case.



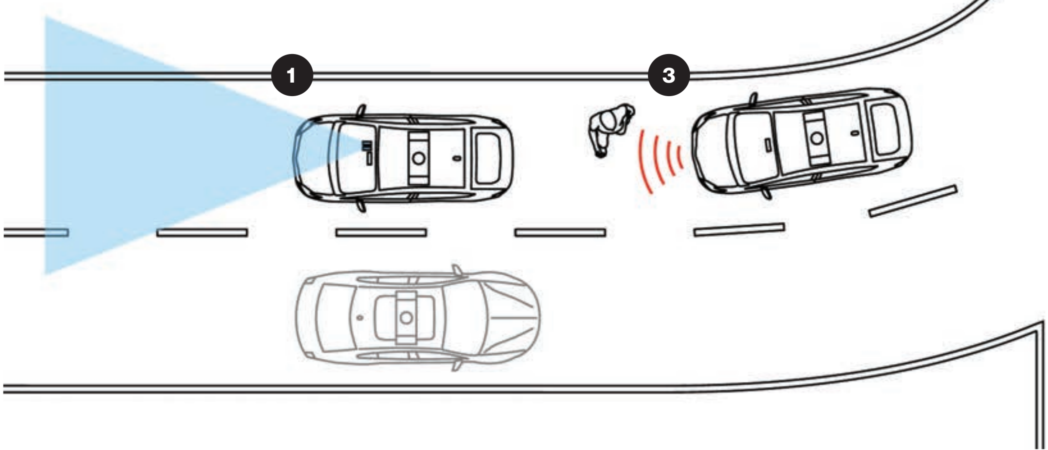
1 Cameras Stereo cameras can help the car see lane markings. Visual data can be fused with data from other sensors to help the vehicle avoid obstacles.

2 Lidar A light detection and ranging system can assemble a very thorough 360° picture of the surrounding environment.



3 Millimeter-wave radar High-frequency radar, installed in bumpers or at intersection control units, can detect pedestrians even under poor lighting and background conditions.

4 Radar Sometimes used today by cruise-control systems to maintain a fixed distance from cars ahead, radar can help maintain the car's position relative to surroundings.



GRAPHIC BY JOHN MACNEILL; DATA FROM JOYCE DARGAY, DERMOT GATELY, AND MARTIN SOMMER; TEXAS TRANSPORTATION INSTITUTE; WORLD HEALTH ORGANIZATION; GOOGLE AND UNIVERSITY OF TEXAS, AUSTIN

Solar-powered microgrids could help bring power to millions of the world's poorest.

A Billion People in the Dark

By Kevin Bullis

The village of Tanjung Batu Laut seems to grow out of a mangrove swamp on an island off the coast of Malaysian Borneo. The houses, propped up over the water on stilts, are cobbled together from old plywood, corrugated steel, and rusted chicken wire. But walk inland and you reach a clearing covered with an array of a hundred solar panels mounted atop bright new metal frames. Thick cables transmit power from the panels into a sturdy building with new doors and windows. Step inside and the heavy humidity gives way to cool, dry air. Fluorescent lights illuminate a row of steel cabinets holding flashing lights and computer displays.

The building is the control center for a small, two-year-old power-generating facility that provides electricity to the approximately 200 people in the village. Computers manage power coming from the solar panels and from diesel generators, storing some of it in large lead-acid batteries and dispatching the rest to meet the growing local demand. Before the tiny plant was installed, the village had no access to reliable electricity, though a few families had small diesel generators. Now all the residents have virtually unlimited power 24 hours a day.

Many of the corrugated-steel roofs in the village incongruously bear television satellite dishes. Some homes, with sagging roofs and crude holes in the walls for windows, contain flat-screen televisions, ceiling fans, power-hungry appliances like irons and rice cookers, and devices that need to run day and night, like freezers. On a Saturday afternoon this summer, kids roamed around with cool

wedges of watermelon they'd bought from Tenggiri Bawal, the owner of a tiny store located off one of the most unstable parts of the elevated wooden walkways that link the houses. Three days before, she'd taken delivery of a refrigerator, where she now keeps watermelon, sodas, and other goods. Bawal smiled as the children clustered outside her store and said, in her limited English, "Business is good."

Worldwide, one and a half billion people lack electricity, most of them rural dwellers. (In India, for example, 268 million people are without electricity in rural areas, but only 21 million in cities.) The International Energy Agency says the type of power plant installed at Batu Laut, known as a hybrid microgrid, will be essential to bringing power to many of them. That's because connecting a remote community to the conventional power grid, with its large, centralized plants, is expensive and can take more than a decade. In some cases, geography and economics may never permit access to the grid. Hybrid microgrids can provide dependable electricity by intelligently combining power from multiple local sources, and building them is far cheaper and faster than extending the grid to the areas where most of the people without electricity live.

Optimal Power Solutions (OPS), the Australian company that designed the microgrid at Batu Laut, is doubling its installations this year throughout Southeast Asia and India. And several other companies, including industrial giants like GE and ABB, are developing and selling similar technology. Microgrids are starting to draw comparisons to cell phones in the developing world, where many poor people never had landlines and went straight to mobile. (In Batu Laut, two derelict, unused pay phones are testaments to the phenomenon.) The hybrid approach, some analysts say, could allow villages to leapfrog the grid in much the same way.

The reality, however, is far more complicated. Some early microgrids have run into problems, and the electricity they provide is more expensive than that from central power grids in the city—in some cases nearly 10 times as expensive. The technology involved in microgrids, and the systems used to operate and maintain them, will need to improve significantly if they are to bring reliable power to hundreds of millions of people.

"The forecast by the International Energy Agency and other groups is that in 20 years, we'll still have a billion and a half people without electricity," says Daniel Kammen, a professor of energy at the University of California, Berkeley, and an advisor for the United Nations' Sustainable Energy for All program. "Microgrids provide an opportunity to think about a really new model of how to bring energy services to off-grid communities. The question is, will this just be a cute development thing? Or will it become part of mainstream economics?"

> *"Microgrids provide [a new way] to bring energy services to off-grid communities. The question is, will this just be a cute development thing? Or will it become part of mainstream economics?"*

WHY IT MATTERS

One and a half billion people, many living in remote areas, have no access to electricity. Microgrids are a practical and relatively inexpensive way to supply them with reliable power.

Power Hungry

It's hard to overstate the importance of electricity for economic and social development. Cooling fans make classrooms more conducive to learning, and lights enable students to read and do homework at night. Refrigerators keep food and vaccines from going bad. A steady supply of electricity can fuel economic development, often starting with modest examples of expanded commerce like Bawal's store. As people make money from such ventures, they can afford more electricity that makes more ambitious projects possible, setting up a cycle of increasing wealth; it's a pattern that economists have documented in country after country. Over the longer term, giving companies access to abundant, reliable, affordable power makes it possible to develop a robust manufacturing sector with such facilities as chip fabs and automotive plants. In the quest to achieve the UN's sustainable-development goals, Secretary-General Ban Ki-Moon has said, "clearly the most important tool will be energy."

Delivering that energy will require some alternative to the conventional grid technology: the IEA estimates that more than two-thirds of rural dwellers who lack electricity today will need power from some sort of distributed source, either microgrids or stand-alone power systems for individual households, because they are far away from the grid or live in a geographically inaccessible area. Yet although hybrid microgrids are a promising solution, the technology is relatively new and unfamiliar, and installing the systems

PREVIOUS SPREAD IMAGE BY CRAIG MAYHEW AND ROBERT SIMMON, NASA GSFC; DATA FROM INTERNATIONAL ENERGY AGENCY AND UNITED NATIONS FOUNDATION

Near the village of Tanjung Batu Laut, a large row of solar panels (right) feeds power to an array of lead-acid batteries (above) inside a building. Diesel generators sitting on the covered deck complete the microgrid power plant.

KEVIN BULLIS/MIT TECHNOLOGY REVIEW

requires a substantial investment. It's not surprising, then, that some of the largest and most advanced microgrids so far can be found in Malaysia, which can afford to be a pioneer. Its economy has been growing impressively for decades, in part because of its oil and natural-gas wealth. And the country's remote islands and large areas of mountainous jungle, including some of the most inaccessible terrain anywhere on earth, often make extending the traditional electricity grid impractical.

"Some parts of interior Malaysia cannot be connected to the grid—they don't have roads. So microgrids are the only solution," says Ramdan Baba, the head of Malaysia's rural electrification programs, speaking from the 23rd floor of a towering office building in a sprawling government district near Kuala Lumpur. The government calculated, for example, that connecting one cluster of villages 130 kilometers from the nearest power line would cost 250 million Malaysian ringgits, or about $80 million. "It's a huge amount of money just to electrify 10 villages with a total of 800 inhabitants," he says. "A microgrid would only cost about 92 million ringgits [$30 million] and provide a reliable 24-hour supply of electricity."

Baba says the government is likely to meet its goal of bringing electricity to 95 percent of the population in Malaysian Borneo by the end of the year (at the start of the project two years ago, 25 percent of that population had no electricity). The technology's success so far has led the government to up the ante. In a bid to bring power to even harder-to-reach areas and electrify 99 percent of Malaysian Borneo, it's planning to increase microgrid installations by 2015.

Now Malaysia's less-well-off neighbor, Indonesia, and other parts of Southeast Asia are starting to use these systems as well. India has experimented with microgrids; its government is considering how the technology could be used more widely in rural areas and to shore up the notoriously unreliable urban grid. In the poorest countries, like Bangladesh, where almost 60 percent of the population lacks electricity, governments and outside funders are currently more interested in smaller-scale sources of power, such as solar-powered lanterns and cell-phone chargers or small solar panels mounted on individual homes. The same is true for African countries such as Kenya, where 84 percent of the population lacks power. Yet solar lanterns fail to bring many of the benefits of a local power network. Microgrids, the IEA concludes in its measured language, "are a competitive solution in rural areas, and can allow for future demand growth."

If the experience in Malaysia is any indication, however, the rollout of the systems could be slow and inefficient, in part because governments and utilities can be leery of new technology. At Batu Laut, the government required OPS to install

600 kilowatts of standby diesel generation capacity, even though the microgrid was designed for a peak load of just 200 kilowatts, because officials weren't sure it would work as advertised. The story may turn out to be similar in India. "It's still a new concept," says Himanshu Gupta, a consultant to the government planning commission in India. "The bureaucrats don't know anything about microgrids."

Moldy Solar Panels

Located in a remote part of northeast Borneo, not far from a deep, cliff-obscured basin that wasn't discovered by outsiders until the 1950s, the village of Kalabakan had no proper paved road until a few years ago, and residents made do with a couple of hours of electricity at night. Three years ago, the Malaysian government funded a microgrid there, and power demand skyrocketed; new customers include a pair of sawmills that service the local logging industry. Unlike its slightly newer counterpart in Batu Laut, however, the microgrid in Kalabakan is already returning to the jungle.

"This place is falling apart," says Ritesh Lutchman, a senior manager at OPS, as he drives onto the grounds of the microgrid power plant. The asphalt road, although it's only a few years old, is deeply gouged and buckling, a victim of Malaysia's soft soil and heavy rains. The solar panels are covered with a thin layer of mold, decreasing power output. Tropical growth is nearly as high as one solar array; in one place it is starting to block the sun. A local utility worker who helps maintain the power station can't find the key to the control room and has to pick the lock with a screwdriver. Inside, it's hot because an automatic cooling fan has failed. Lutchman suspects that the heat could be damaging the expensive equipment, shortening its life.

Worse, half the microgrid isn't even getting power. Because the output of its diesel generators wasn't synchronized, only one generator can run at a time, and one can't provide enough electricity to power both of the distribution networks that deliver electricity. Lutchman didn't know about the problem because, days before, local workers had disconnected the data hub that was the only communication link between the microgrid and OPS. The workers were using it to surf the Web, something Lutchman learned about only when OPS got a large bill.

As microgrids bring power to remote areas, villagers plug in TVs, stereos, and appliances such as refrigerators (upper left), and a convenience store owner starts selling popsicles (bottom). A sawmill runs on one microgrid (upper right).

KEVIN BULLIS/MIT TECHNOLOGY REVIEW

The trouble at Kalabakan reflects a deeper problem: there is no practical model in place for maintaining and operating a microgrid. The government pays for the system; companies such as OPS design it, install it, and keep it working during a two-year warranty period; and then, in the case of Malaysia, they turn over control to the local utility, which is what happened at Kalabakan. While OPS still monitors the microgrids it has installed, after the first two years it is no longer paid to maintain them.

The utilities aren't set up for microgrids, Lutchman says: "Sometimes the utility will call in someone who understands generators, but he doesn't understand how they connect to the rest of the system." The current partial power outage happened after a diesel generator was taken offline for a regularly scheduled overhaul. When it was reconnected, its voltage output wasn't adjusted to fall within the specifications of the microgrid's automatic control system. Fixing that is a simple adjustment, Lutchman says, but one the local utility workers didn't know to make. The utilities didn't even ask for the microgrids, he says. They were just given them, without the training they would need to maintain them.

The World Bank recently issued a report that warns of some of the challenges. Pepukaye Bardouille, a senior operations officer at the agency's International Finance Corporation, says her group is "excited" about microgrids, but they're "trying to inject a dose of realism." Bardouille explains, "What tends to happen is a few examples are touted as a solution on the basis of technology or just cost. But ways to deliver the technology and maintain it are actually so much a part of the solution that if those things aren't dealt with, it's just not sustainable."

Ramdan Baba says his government is working on a new way to fund and maintain microgrids. The company that designs and installs the technology will be given a license to operate it and receive a guaranteed price for the power it produces; it will make a profit only if it can keep costs under control and keep the grid producing power for the length of the contract.

Unlike its slightly newer counterpart in Batu Laut, the microgrid in Kalabakan is already returning to the jungle. Tropical growth is nearly as high as one solar array; in one place it is starting to block the sun.

This summer at OPS's Malaysia headquarters in Kuala Lumpur, the company's engineers and managers were busy with phone calls, meetings with government officials, and last-minute calculations. The key issue was estimating the cost per kilowatt-hour of the electricity the microgrid produced, which would be key to establishing the price OPS and other companies would get paid. Too high and OPS would reap a windfall at the expense of the Malaysian government; too low and the company would be stuck maintaining a money-losing operation.

Battery Problems

Microgrids face another looming problem, this one technical. Solar panels and diesel generators can last for decades, but the batteries that make them possible fail much more quickly. "With a microgrid, you typically need an energy storage system that, with current technology, you have to replace every three or five or seven years. That's a huge capital cost," says Katherine Steel, an MIT-trained engineer who heads the World Bank's Lighting Africa program. If replacement batteries are not in the budget, the effective lifetime of the microgrid is limited to only a few years.

According to OPS, lead-acid batteries keep the price of microgrids relatively high not only because they need to be replaced frequently but because they are so expensive that microgrid designers lean heavily on diesel generation to provide electricity through the night. It is cheaper to run diesel generators than to add enough solar panels and batteries to provide power around the clock. To overcome this problem, OPS is now testing a battery from Aquion, a Carnegie Mellon University spinout in Pittsburgh; it could nearly eliminate the need for diesel in microgrids, lowering emissions and greatly reducing operating costs.

"Microgrids still use a fair amount of diesel," says Jay Whitacre, a Carnegie Mellon professor who invented Aquion's technology. "The next step is to go to a situation where they have a diesel generator present, but they almost never are turned on. Our battery could allow that." The Aquion batteries work much like the relatively long-lived lithium-ion batteries used in electric cars, which are much more expensive than lead-acid batteries. But the company's technology uses far cheaper materials and is easier to manufacture, keeping costs competitive with the less

In Borneo, in the midst of vast palm-oil plantations, the electricity grid comes to a sudden stop. The government is expanding the grid wherever it makes economic sense.

KEVIN BULLIS/MIT TECHNOLOGY REVIEW

durable batteries that are now widely used in microgrids. "Our battery will cost about as much as a high-quality lead-acid battery up front," he says. "But that lead-acid battery is going to have to be kept cooler, and it's going to have to be swapped out after a couple of thousand cycles. Ours will go way more than that—two or three times as long."

The savings from cutting diesel consumption could be significant. The microgrid at Batu Laut is designed to get much of its power from diesel, but a system designed around cheaper batteries might need generators only for emergencies and long stretches of bad weather. Reducing battery costs and diesel consumption could lower the cost per kilowatt-hour from a dollar to as little as 40 cents.

Yet even that is higher than the price of electricity from the grid. The Malaysian government subsidizes microgrid electricity so that villagers pay something comparable to city rates, but it can't keep doing that forever, in part because with each additional kilowatt-hour villagers consume, the cost of the subsidies goes up. In poorer countries like India, the high cost of microgrid power could be an even bigger obstacle to widespread deployment.

"For microgrids to be a leapfrogging technology like cell phones, they would have to offer equivalent or superior service to the grid at a lower cost," Steel says. "But I think that's a transition that still needs to take place, and I wouldn't say that's immediately around the corner."

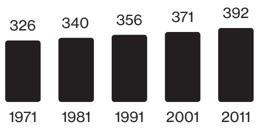
A more likely scenario is that microgrids and the conventional grid will complement each other. As the conventional grid expands from cities and as improved roads make communities less remote, extending the grid to them will make more economic sense. Where microgrids exist, many will eventually be absorbed into the larger power grid. At times of peak demand, utilities can call on electricity stored in microgrids' batteries or use their diesel generators to provide a boost of power. If this happens, hybrid microgrids will make the existing grid far more resilient. Indeed, as battery costs decline, microgrids are an increasingly attractive option in cities where conventional grid power is unreliable; they could ensure that factories and other users have a dependable source of electricity.

These types of large infrastructure changes will take years and require significant investments. Meanwhile, though, microgrids have already begun to make a difference to some lives. Back at Batu Laut, the system continues to hum quietly along, and villagers are getting new ideas about how to use the electricity. One woman has acquired an embroidery machine and hopes to sell customized uniforms. The head of the village's development committee is lobbying for a government grant to build a food-processing factory that would run on power from the microgrid. And now that the village has reliable electricity, the teachers for the local school are moving out of the city on the mainland to live on the island. T

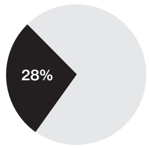
Kevin Bullis is MIT Technology Review*'s senior editor for energy.*

Carbon Capture

Atmospheric levels of carbon dioxide (parts per million)



Percent of U.S. carbon dioxide emissions from transportation

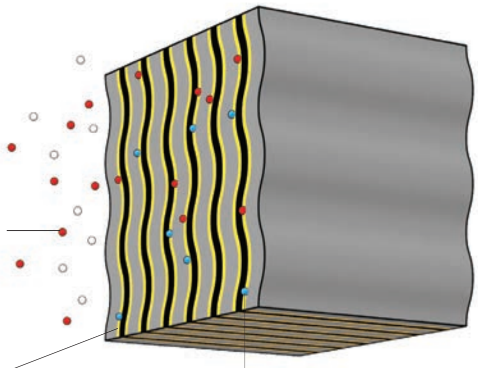


Global emissions of carbon dioxide from fossil-fuel combustion, in metric tons

31.6 billion

Capture material
The surfaces of a corrugated-plastic material are wetted with a carbon-dioxide-absorbing solution (yellow) that flows down through the stacks.

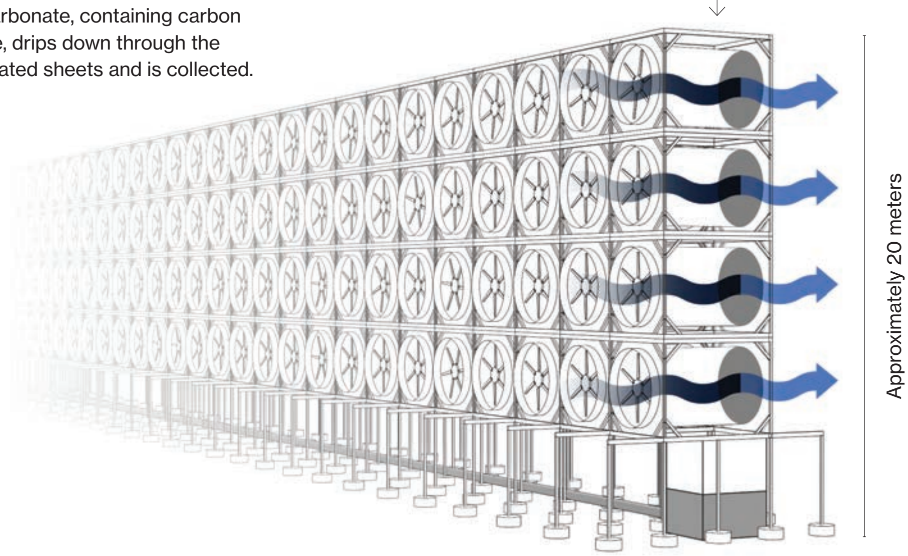
Carbon dioxide



Air contactor
Large fans push air through the corrugated sheets. At the bottom, the carbonate liquid is collected and funneled into a sump. This is processed; concentrated carbon dioxide is produced and purified; and the original carbon-dioxide-absorbing solution is regenerated and can be reused.

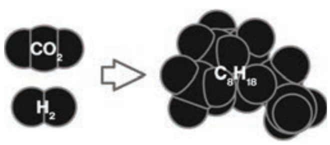
Carbonate liquid
When carbon dioxide contacts the liquid, it reacts with it and forms a carbonate solution.

Trapped carbon dioxide
The carbonate, containing carbon dioxide, drips down through the corrugated sheets and is collected.



The amount of carbon dioxide in the atmosphere continues to rise. And since cleaner energy sources are replacing fossil fuels to only a limited extent, scientists are looking for ways to mitigate carbon dioxide emissions. The gas can be captured at power plants before it goes into the atmosphere, but that method won't work in car tailpipes. So Carbon Engineering, a company based in Calgary, Alberta, and founded by Harvard physicist David Keith, has come up with a way to capture carbon dioxide that has already been released into the air. It involves stacks of structures in which the gas gets trapped in a liquid solution. The collected carbon dioxide can be sequestered or used in industrial applications. It's a relatively simple process that could be used in very large units that would capture the carbon emitted by hundred of thousands of cars. Carbon Engineering hopes that the captured carbon could someday be combined with hydrogen to produce hydrocarbon fuels.

Carbon-neutral fuel



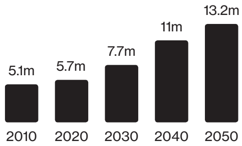
Eventually, if the economics are favorable, the captured carbon dioxide could be combined with hydrogen to make fuel. When burned, this would return the same carbon to the air.

GRAPHIC BY JOHN MACNEILL. DATA FROM NOAA; INTERNATIONAL ENERGY AGENCY; ENERGY INFORMATION ADMINISTRATION.

Blue Skies, 1995
oil on canvas, 152 x 122 cm

The first self-portrait completed after his diagnosis shows a man whose world has become untethered. The artist clings to a table as if to anchor himself within a flattened, featureless space.

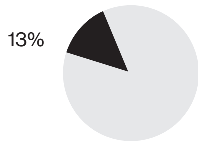
Actual and expected number of Americans 65 and over with Alzheimer's



People worldwide with dementia

36 million

Percentage of Americans 65 and older with Alzheimer's



ABOUT THE ARTWORK: *When he learned in 1995 that he had Alzheimer's disease, William Utermohlen, an American artist living in London, immediately began work on an ambitious series of self-portraits. The artist pursued this project over an eight-year period, adapting his style to the growing limitations of his perception and motor skills and creating images that powerfully documented his experience of his illness. The resulting body of work serves as a unique artistic, medical, and personal record of one man's struggle with dementia.*

By STEPHEN S. HALL

The Dementia Plague

As the world's population of older people rapidly grows in the coming years, Alzheimer's and other forms of dementia will become a health-care disaster.

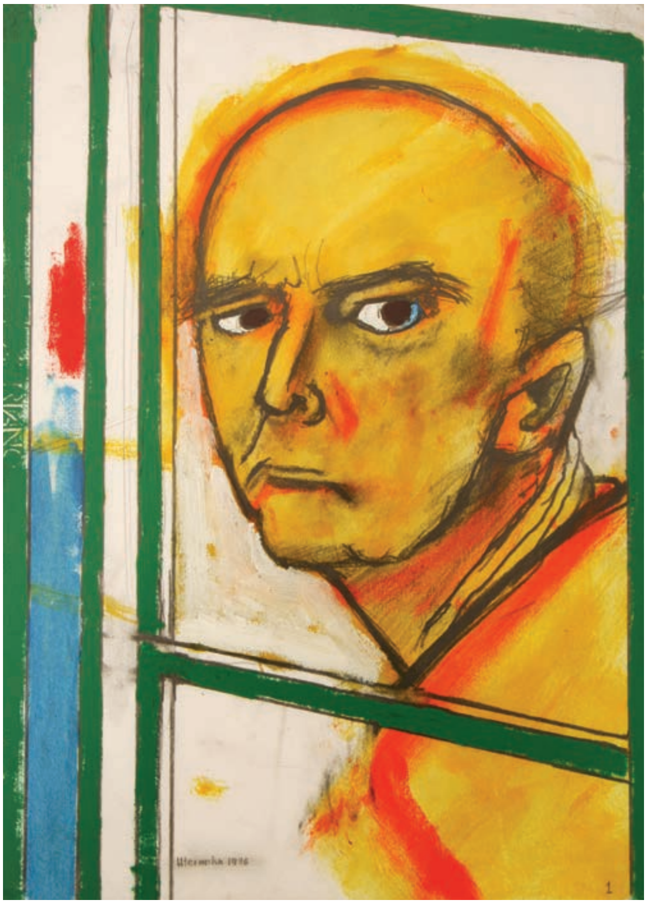
EVELYN C. GRANIERI IS THAT RAREST OF 21ST-CENTURY DOCTORS: she still makes house calls. On a warm Thursday morning toward the end of August, the New York–based geriatrician, outfitted in a tailored white suit and high heels, rang a doorbell at a seven-story red-brick apartment building in the Riverdale section of the Bronx and was buzzed in.

"You look gorgeous!" the doctor exclaimed when she greeted her patient, a 99-year-old woman with white hair and a wry smile, in the dining room of her apartment. In an hourlong conversation, Mrs. K (as we'll call her) recalled, in moving and sometimes mischievous detail, growing up in Poland, where soldiers on horseback took her brother away; coming to America on a ship and working in her parents' grocery story in Queens; and dealing with male colleagues in the real-estate business when they got "fresh." But when Granieri asked how old Mrs. K was when she got married, she looked puzzled.

"I can't remember," she said after a pause. A cloud passed over her face. "Was I married? To whom?" A framed photograph on a nearby table memorialized her 50th wedding anniversary.

Spirited and funny, her personality intact even as her memory deteriorates, Mrs. K is one of more than five million Americans with dementia. Far from the gleaming research centers where

Self-Portrait with Easel (Yellow and Green), 1996
oil on canvas, 46 x 35 cm



scientists parse the subtle biochemical changes associated with Alzheimer's disease and other forms of the condition, clinicians like Granieri, chief of the Division of Geriatric Medicine and Aging at Columbia University Medical Center, confront its devastating reality every day. And, often, they talk to relatives of patients. As Granieri and two interns probed Mrs. K's memory with small talk and measured her blood pressure, a niece called from Manhattan to see how her aunt was doing.

Almost every dementia patient has worried family members huddled in the background, and almost every story about dementia includes a moment when loved ones plead with the doctor for something—any medicine, any intervention, anything—to forestall a relentless process that strips away identity, personality, and ultimately the basic ability to think. Unfortunately, Evelyn Granieri is the wrong person to ask. In 2010 she served on a high-level panel of experts that assessed every possible dementia intervention, from expensive cholinesterase-inhibiting drugs to cognitive exercises like crossword puzzles, for the National Institutes of Health; it found no evidence that any of the interventions could prevent the onslaught of Alzheimer's. She can—with immense compassion, but equally immense conviction—explain the reality for now and the immediate future: "There really is nothing." Dementia is a chronic, progressive, terminal disease, she says. "You don't get better, ever."

These conversations have always been difficult for doctors and families alike, but perhaps never more so than in the past year, when public reports about dementia research have bounced between optimism and gloom. In the fall of 2011, financial analysts were giddily projecting a global Alzheimer's market of $14 billion a year by 2020 and touting a new generation of drugs known as monoclonal antibodies that were in advanced human trials. A year later, the prospect for the drugs no longer looked so positive. This past August, the giant drug makers Pfizer and Johnson & Johnson suspended advanced clinical trials of one of the monoclonals because it showed no effect in patients with mild to moderate Alzheimer's. A few weeks later, another leading pharmaceutical manufacturer, Eli Lilly, announced inconclusive results for a monoclonal drug it too was testing against the protein deposits called amyloid plaques that are characteristically found in the brains of Alzheimer's patients. The disheartening results prompted some critics to start writing epitaphs for the prevailing hypothesis about the disease—that these amyloid deposits are causing the cognitive impairment.

"The field is in a precarious place right now," says Barry D. Greenberg, director of strategy for the Toronto Dementia Research Alliance, "because tens of billions of dollars have been invested in the development of new treatments, and nothing—not a single disease-modifying agent—has been identified."

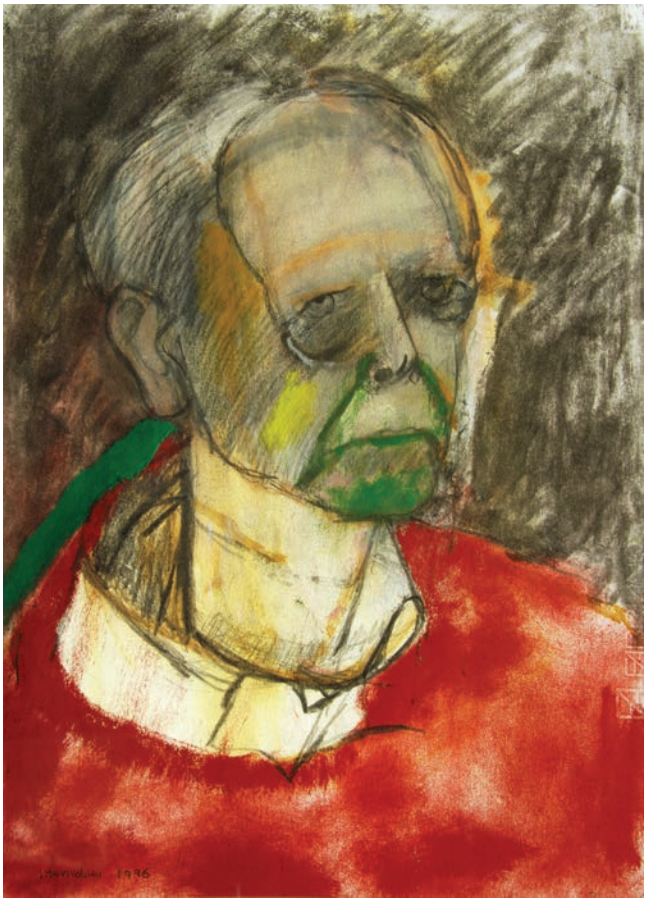
Granieri often sets off on her house calls from her second-floor office at Allen Hospital—literally the last building in Manhattan, on the northernmost tip of Broadway. That may sound like an out-of-the-way outpost in medicine's battle against dementia, but in reality it sits at ground zero for the looming medical and societal catastrophe. The hospital's catchment area includes upper Manhattan and parts of the Bronx, one of the three densest concentrations of nursing home facilities in the entire United States, according to Granieri. "Here we sit, right in an epicenter," she says.

The epicenter is a contentious place these days. Frontline clinicians like

WHY IT MATTERS

We have no effective treatments for dementia, a huge health crisis facing the world. The annual cost of care in the United States alone could reach $1 trillion by 2050.

Self-Portrait (Red), 1996
mixed media on paper, 46.5 x 33 cm



Granieri are increasingly frustrated with the narrowness of dementia research. In the patients they treat every day, they see a disease that is complicated and insidious, often with multiple causes and murky diagnostic distinctions. In contrast, they see a research enterprise focused on several favorite hypotheses, and they see a drug industry that has profited handsomely from expensive, marginally effective treatments sought by desperate families.

Academic and pharmaceutical researchers, meanwhile, continue to throw money at the dementia problem—but finally, they insist, with better aim and much shrewder treatment strategies. They have begun to assemble a list of diagnostic markers that they believe may reliably indicate the first signs of Alzheimer's disease 10 or 15 years before symptoms appear, and they are gearing up to test new drugs that can be given to healthy patients, in an attempt to block the buildup of amyloid long before dementia's onset. Indeed, to hear researchers tell it, this summer's highly publicized clinical-trial failures are already ancient history. They are finally doing the right kind of science and hope to get the right kinds of answers, the first glimpses of which may appear in the next several years.

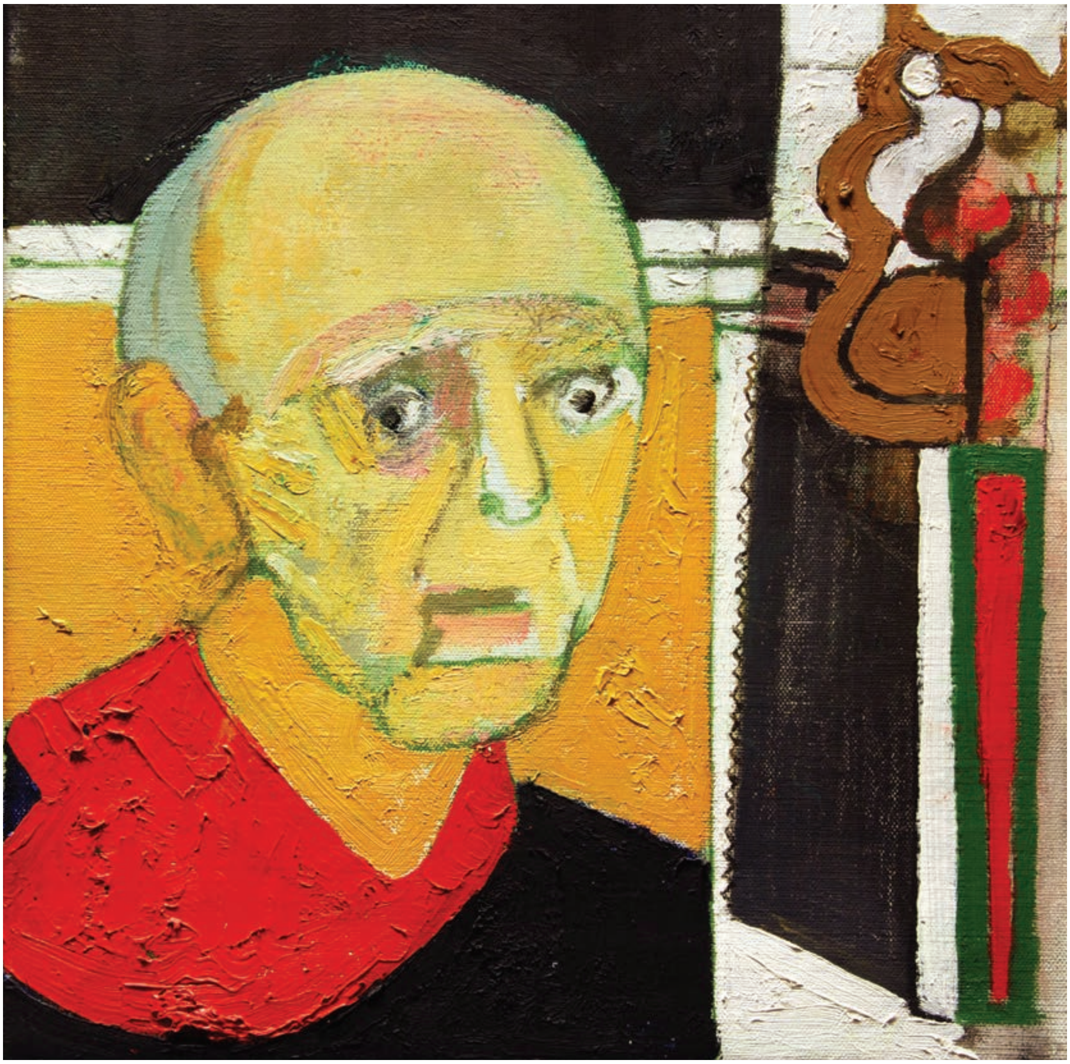
As Granieri and other physicians who treat dementia patients know, the stakes could scarcely be higher.

Tangled Connections

IN OCTOBER 1986, ONE YEAR AFTER HIS GRANDMOTHER Sadie died of dementia in a New York City nursing home, Barry Greenberg cloned a gene he thought would be key in the battle against Alzheimer's disease. Ever since the German physician Alois Alzheimer first described the pathological hallmarks of his namesake disease in 1906, scientists have focused on two prominent physiological features that snarl the brains of dementia patients: plaques of the gummy protein amyloid beta, which build up outside brain cells, and hairy tangles of protein inside neurons (these tangles are now known to be misshapen versions of a normal protein called tau). Greenberg, then working at a West Coast startup called California Biotechnology, had found the gene for amyloid precursor protein, which tells the body how to make the protein that ends up as the amyloid plaques. He excitedly called his father with the good news, and his father replied, "That's wonderful, son. Now what's left to be done?"

A quarter-century later, after stops at five pharmaceutical companies and countless twists and turns in the research saga, Greenberg can tell the anecdote with a chuckle, but the larger story is no laughing matter. He has seen this emerging medical disaster as a bench scientist, as a pharmaceutical-industry insider, and now as a coördinator of clinical research and drug development for an alliance of Canadian hospitals and memory clinics associated with the University of Toronto, which serve some 7,000 dementia patients a year. In a recent talk to a lay audience on Prince Edward Island, he spoke about his grandmother's illness and then dropped the hammer. "The scope of the looming medical-care disaster," he said, "is beyond comparison with anything that has been faced during the entire history of humanity."

The latest global demographic analysis, from a World Health Organization report issued earlier this year, paints the dimensions of that slow-motion catastrophe in quick strokes. An estimated 36 million people worldwide currently suffer from dementia; experts predict the number will double, to approximately 70 million, by 2030 and triple by 2050. (China, India, and Latin America in particular face daunting medico-economic crises.) Since the prevalence of the disease doubles with every



Self-Portrait (with Saw), 1997
oil on canvas, 35.5 x 35.5 cm

In 1997, the artist learned that his doctors would be unable to definitively diagnose his disease until autopsy. The saw depicted here is an open allusion to this fact.

five-year age increment after 65, projections for 2050 put the total global population at risk for dementia (people 65 or older) at two billion. The calculus is as grim as it is simple: as more people live longer, more slide into dementia. Care for those patients currently costs $100 billion a year in the United States, with a projected cost over the next 40 years of $20 trillion; by 2050, the cost to U.S. society is projected to be $1 trillion a year.

An even more sobering perspective on the problem comes from a small unpublished pilot study that Granieri and her colleagues at Columbia recently undertook. They did a standard cognitive evaluation of every person 70 or older who was admitted to Allen Hospital for any reason—heart problems, pain, diabetes, breathing difficulties. The results stunned them. "In this hospital, of patients 70 years of age or older, 90 percent have cognitive impairment of some kind, which is much higher than we anticipated," she says.

Not only is dementia distressingly widespread, but the complex overlap of symptoms and possible causes makes addressing the problem broader and trickier than just treating Alzheimer's. The emerging reality, which has become increasingly apparent with better brain imaging, is that the majority of cases among the elderly are so-called "mixed dementias"; the cognitive impairment is due to a combination of vascular problems, such as mini-strokes in discrete parts of the brain, and the more classic Alzheimer's pattern of amyloid plaques. Large-scale international studies in the past three years have shown, according to a recent scientific summary, that dementias caused by blood-vessel lesions in the brain, including vascular dementia and mixed dementia, "together comprise the most common forms of dementia at autopsy in community-based studies."

Sharon Brangman, a physician who finished a term as chair of the board of the American Geriatrics Society earlier this year, especially welcomes the message that Alzheimer's in particular, and dementia in general, is much more complex than the focused research of the last 20 years would suggest. "When you've lost something, and you've looked in all the obvious places and you still haven't found it, you need to start looking in other places," she says. "Not everyone with Alzheimer's has the same clinical presentation, and there's more to dementia than Alzheimer's disease. We have a broad disease category that people can enter from multiple avenues. But we are attacking dementia now from only one narrow entry point. It's going to be more complicated than that. Right now, we have a one-size-fits-all approach to dementia."

In order to come up with more effective drugs, scientists need to understand exactly how each kind of dementia develops and how to attack that specific disease process. Much of the research has so far focused on Alzheimer's disease. And yet the basic biol-

On Living with Dementia

By Floyd Skloot

I first turned 65 when I was 41. Geezered almost overnight after a viral attack to my brain in 1988, I was soon diagnosed with static dementia, displaying classic multiple cognitive deficits, including memory impairment. Most people who become demented do so over time, fading, their symptoms developing. Mine happened suddenly and didn't progress. At least, they haven't for the last 24 years.

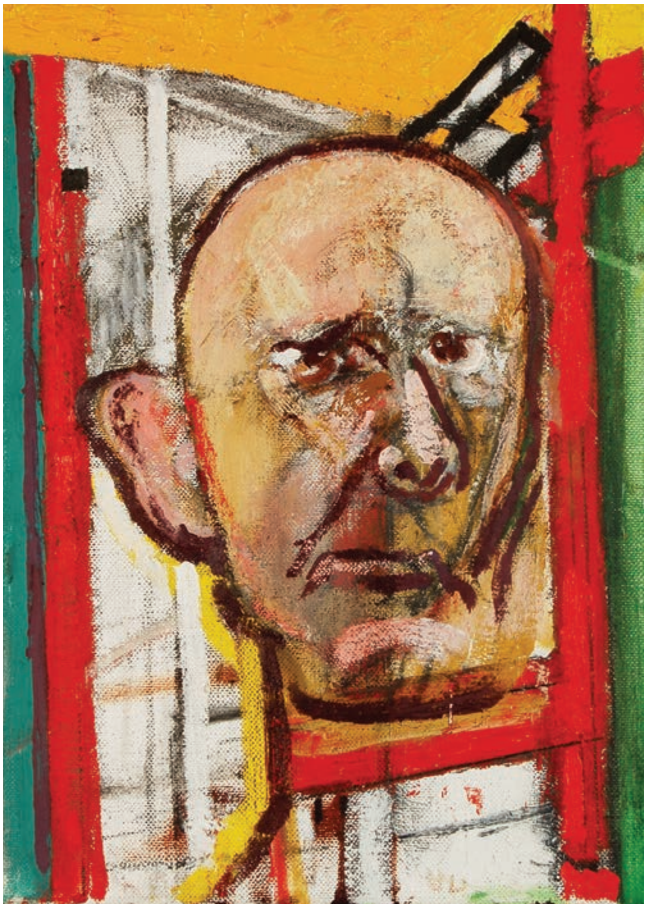
A few months ago, I turned 65 again—this time chronologically—and it's like I've had more than a third of my life to get used to the sorts of declining powers that I'd be likely to face now anyway. I still commit the sorts of mistakes, neurocognitive snafus, that have marked my shattered functioning. Just this week, I put a capsule into the espresso machine, removed the empty cup I'd just placed under the spigot so there was now nothing in which to catch the liquid, pressed the Start button, and watched in bafflement as rich, dark brew spewed over the kitchen counter. This was matched, two days later, by pouring juice into a cereal bowl rather than a glass and watching in wonder as the purple spread more widely than it was supposed to.

Last night I announced to my wife, Beverly, that I'd *numbed* the television rather than *muted* it, and that I would *evaporate* rather than *delete* a film we'd just watched on our DVR. Earlier today, by the time I reached for one of the pens and notepads I keep all around our home, I could no longer remember the item I'd wanted to add to our shopping list. The problem was that I allowed myself to think I needed to find the pen and notepad when I should have kept focused on whatever it was I wanted to write down. Unfortunately, all this leads to a life filled with loony babble, because under stress I tend to say out loud what I'm trying to remember as I try to find the pen and paper whose whereabouts I can't remember. In some ways, it's comforting—in the sense of making me feel less alone and difficult to be with—that my wife began doing the same sorts of things as she neared 60.

Something I wrote 15 years ago about living with dementia became a credo for me: since I can't presume I'll remember anything, I must live fully in the present. Since I can't presume I'll understand anything, I must experience my life without pressing to formulate ideas about it. Since I can't escape my altered brain and the limits it has imposed, I must be at home with it. And since I can't presume I'll master anything I do, I must let go of mastery as a goal and seek harmony instead.

Floyd Skloot's books include The Wink of the Zenith: The Shaping of a Writer's Life *and* In the Shadow of Memory*, an account of the aftermath of his 1988 illness.*

Self-Portrait (with Easel), 1998
oil on canvas, 35.5 x 25 cm



ogy of even that most well-studied form of dementia remains fuzzy. Are the amyloid plaques the key pathological factor, as a large body of research suggests, or is it the thickets of aberrant proteins known as tau tangles, which appear in dementia patients after the plaques do? If amyloid leads to tau tangles, how are they related? Or, as an alternative hypothesis suggests, is dementia somehow connected to impaired processing of blood sugar? (This possibility was endorsed by the NIH's recent decision to support a University of Washington clinical trial of a nasal insulin spray.) Or does the actual cause of Alzheimer's have something to do with an imbalance of metal ions in brain cells, which is the animating idea behind advanced clinical trials by an Australian biotech company?

The persistence of so many hypotheses suggests that neither clear-cut evidence nor consensus for one theory of disease has yet emerged. "I think you have to continue to look at these hypotheses," says Granieri, "but they *are* hypotheses, and [researchers] have to be honest about that."

Demented Mice

ONE RECENT AFTERNOON, IN A NEWLY RENOVATED 12TH-floor research complex in Columbia University's College of Physicians and Surgeons, Alzheimer's researcher Karen Duff inspected several elderly mice sitting in cages on a shelf in her lab. These were, in lab parlance, tau mice. They had been genetically engineered to produce abnormal human tau protein in a very specific part of their brains, the same small place where autopsies have shown that it first appears in human brains. One mouse in particular stood out because of its ragged, ruffled brown fur.

"This one may be a bit demented," Duff said matter-of-factly. "It's a little less well-groomed, and one of the first signs [of dementia] is a rougher fur." If these mice mimicked the pattern of pathology seen in humans with dementia, Duff added, the misshapen protein "would have spread to areas of the brain affected by Alzheimer's disease." The confirmation came a few days later, when technicians sacrificed the animals and mapped tangled bits of malformed tau that had spread throughout their brains. It is these tangles, according to Duff, that eventually kill the cells that confer memory, perception, cognition.

The mice on Duff's lab shelf and their experimental brethren have introduced a surprising new wrinkle to the pathology of Alzheimer's. Duff and her colleagues have conducted experiments showing that misshapen tau proteins initially sequestered in the part of the brain where Alzheimer's typically first appears (the entorhinal cortex) somehow were able to spread along nerve circuits and hop across synapses to other parts of the brain long known to be involved in dementia, including the hippocampus. As these abnormal tau proteins spread through the brain, they "usurped" and corrupted the normal tau proteins in affected cells, inducing lethal tangles and killing neurons.

The good news is that this mechanism offers novel opportunities for treatment: attacking abnormal tau as it hops between cells. The Columbia group is already conducting animal tests of a monoclonal antibody designed to intercept tau at precisely this vulnerable point of passage, and Duff says pharmaceutical companies have shown considerable interest in the model.

But the new findings are also a stark reminder of how much researchers still need to learn about Alzheimer's in particular and dementia in general. The scientific literature now describes amyloid as necessary but not sufficient to explain Alzheimer's symptoms, yet despite intense investigation, there is no general agreement on the mechanism linking the two signal features

Erased Self-Portrait, 1999
oil on canvas, 45.5 x 35.5 cm

of a brain in the throes of the illness. Scientists still don't know why the amyloid plaques precede the tau tangles by anywhere from 10 to 20 years, and they don't know how the two pathologies are connected. "We know amyloid protein builds up, but there's a lot of debate if it's the chicken or the egg, if that's the trigger or the result of the disease," says Brangman.

Even after decades of discussion about the role of amyloid in Alzheimer's disease, researchers concede, the hypothesis that these plaques are key to the illness has not been properly tested. "We haven't tested the right patients at the right time with the right agents," says Greenberg. "The reality is that we haven't done that yet. But the field knows what to do and is doing it now."

Indeed, several ambitious clinical trials—Greenberg considers them the most important trials in the history of Alzheimer's drug discovery—are poised to launch in the next few months, and the results will shape dementia research for years to come. If these so-called prevention trials succeed, they will hold out hope that the usually inevitable course of dementia can be altered. If they fail to modify the course of the disease, however, the implications will be what researchers like Greenberg and Duff call "devastating" and "horrendous."

True Test

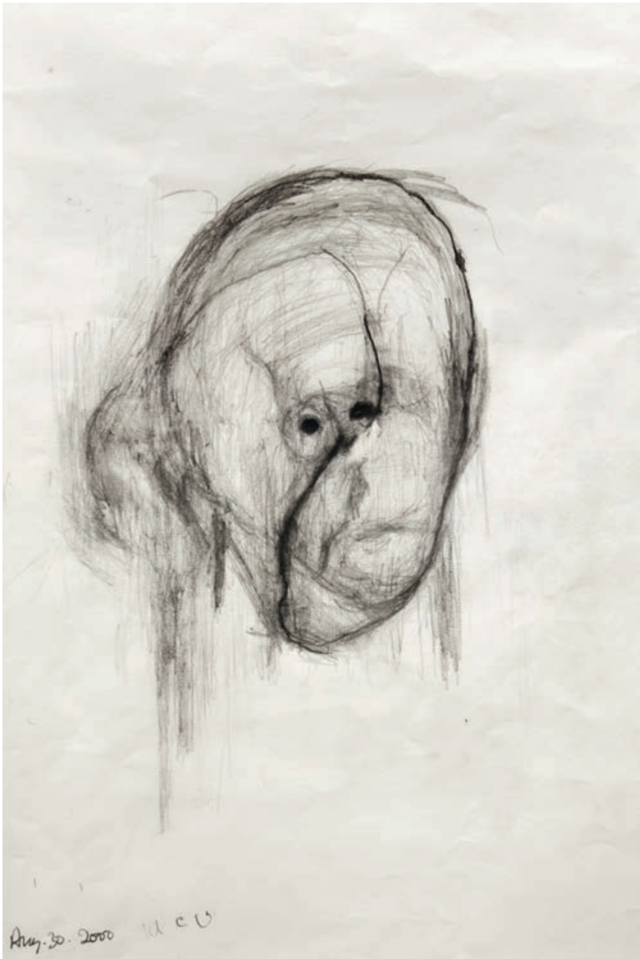
GIVEN THE MAGNITUDE AND URGENCY OF THE PROBLEM, it's no wonder that when Kathleen Sebelius, the U.S. health and human services secretary, announced new NIH funding last February, she told reporters, "We can't wait to act." And yet it's clear to many experts that we probably will wait for an effective Alzheimer's drug—perhaps as long as 10 or 15 years.

The challenge of finding a treatment that will alter the course of dementia is daunting precisely because the process of neural degradation proceeds invisibly for so many years and starts so early. How early? Last July, the Dominantly Inherited Alzheimer's Network, a network of leading academic centers based at Washington University in St. Louis, published surprising findings that detectable changes in amyloid chemistry in patients with a genetic form of Alzheimer's may appear in a person's cerebral spinal fluid up to 25 years before the onset of Alzheimer's symptoms. By the time Alzheimer's patients show up in the neurologist's office with signs of mild or moderate dementia, it is too late.

If the amyloid hypothesis for Alzheimer's is correct, therefore, researchers need to find and treat patients a decade or more before the first signs of cognitive impairment appear. They need a drug that crosses the blood-brain barrier to disrupt the buildup of amyloid. And they need diagnostic tools—the cognitive and neural equivalent of a glucose test for diabetics—to measure changes in amyloid and other biomarkers to determine if the therapies are working. (These same diagnostic markers might also be used to identify patients at risk for Alzheimer's who would benefit from preventive treatment.) Although progress has been made in finding these markers, their reliability is still uncertain. The Food and Drug Administration could speed up drug approvals on the basis of improvements in them, says Sam Gandy, director of the Mount Sinai Center for Cognitive Health in New York. But everyone will still be "holding their breath" until patients are "well beyond the age at which they would be expected to be at risk of becoming demented."

The group of researchers based at Washington University has assembled a promising tool kit to help them detect the progress of the disease: brain imaging of amyloid deposits, analysis of cerebral spinal fluid, and cognitive tests. But who should the test subjects be? As it turns out, there are several rare genetic forms of Alzheimer's, and these have been the network's longtime research focus. People who inherit very specific dominant mutations are fated to develop Alzheimer's at a relatively early age,

Head I, 2000
graphite on paper, 40.5 x 33 cm



and researchers can calculate when the first symptoms of the disease are likely to appear. The network is now in the final stages of selecting three distinct therapeutic agents that target amyloid, with plans to test them in patients with genetic forms of Alzheimer's.

Randall Bateman, a Washington University physician and researcher, says the aim of the study is to find a drug that will curtail the buildup of amyloid in the brain, much as doctors use statins to reduce the risk of stroke and heart attack by lowering cholesterol levels. Bateman says his research group hopes to launch human tests using the biomarkers by early 2013; he and his colleagues hope to see evidence of effects on these markers after two or three years of treatment rather than waiting 10 or 15 years, when symptoms of dementia would be expected to appear.

The other closely watched trial will be launched—with the NIH's blessing and funding—by the Banner Alzheimer's Institute in Phoenix and Genentech. Most of the patients in this trial also have a genetic form of the disease. Members of an extended family of some 5,000 people living in the Antioquia region of Colombia are at risk for a very rare mutation; those who are carriers invariably develop an early-onset version of Alzheimer's. The idea is to treat about 300 members of this group with an experimental drug to attack amyloid plaques an estimated 15 years before symptoms would be anticipated.

The drug, licensed by Genentech, is an amyloid-attacking monoclonal antibody called crenezumab. Doctors believe it can safely be injected at a higher dose than other monoclonal drugs. "We believe the higher dose will translate into higher efficacy," says Carole Ho, group medical director for early clinical development at Genentech.

In administering these drugs earlier, to a population genetically susceptible to the disease, Alzheimer's researchers believe they are finally giving the right kind of therapy to the right patients at the right time. And given the stakes, the two prevention trials have sparked high anticipation. "This will be the first true test of the amyloid hypothesis," says Barry Greenberg. "The strategy is sound. So let the data happen."

If the prevention trials succeed, however, there's no guarantee that this version of early intervention will help in most cases of dementia. Clinicians warn that these rare, early-onset, mutation-based forms of the disease account for at most 10 percent of all Alzheimer's cases. As Evelyn Granieri puts it, "This may not even be the Alzheimer's disease that the majority of people get."

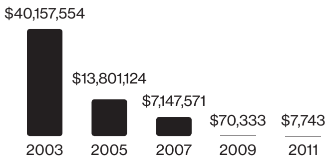
The genetic forms of the disease are similar in pathology to the forms most people do get, Ho says. Still, even positive results gleaned from early interim analyses of these trials would come too late for the millions of people who have already begun the slow descent into cognitive decline. "The reality," says Granieri, "is that most people who are around and sentient now are not going to be around for the cure." All the more reason, according to Greenberg, to adopt "fundamentally different thinking" in dementia research. "The medical-care system is going to be bankrupt by 2050 if we don't figure out a way to delay or treat Alzheimer's disease," he says, and he believes that won't happen without a major public-private international initiative. "The competitive marketplace," he says, "was not conceived to overcome problems of this magnitude."

Stephen S. Hall's latest book is Wisdom: From Philosophy to Neuroscience *(Vintage). His last story for* MIT Technology Review *was "The Genome's Dark Matter" (January/February 2011).*

SOLUTIONS • DISEASE

Cancer Genomics

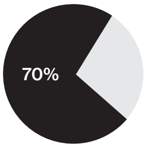
Cost of sequencing an individual's genome



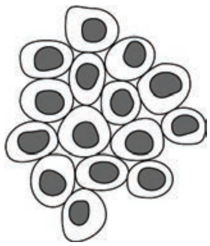
Number of people killed by cancer in 2008

7.6 million

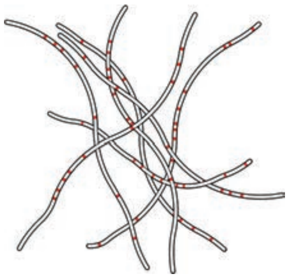
Percentage of tumors with genetic changes that could inform treatment



Cancer is driven by changes in the genomes of tumor cells. By sequencing the DNA of these cells, physicians can diagnose and, in some cases, treat the cancer more effectively. The information may help identify drugs that are likeliest to help a patient, or rule out ones that won't work. One company helping to push cancer genomics into medical practice is Foundation Medicine. Send the company a tumor sample and its researchers will examine hundreds of the cancer's genes, looking for mutations that have been targeted by drugs either on the market or in clinical trials. The plunging cost and accelerating speed of DNA sequencing have made this type of genetic analysis practical for the first time.

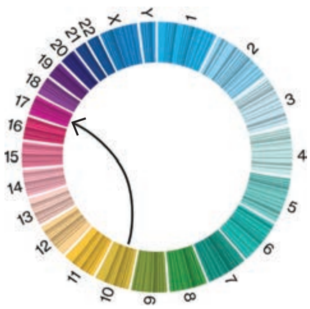


1. The process starts with a small piece of a patient's tumor that is biopsied.

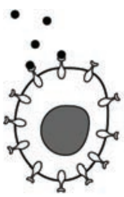


2. After extracting DNA from the tumor sample, Foundation Medicine separates the genes known to be involved in the growth of cancer.

3. These genes are then sequenced and analyzed to identify mutations. Sequencing only a subset of genes makes the testing less time-consuming.



4. A diagram can be used to show changes in a cancer's genome. In one type of change, seen here, DNA may move from one chromosome to another.



5. If such changes cause certain molecular disruptions, such as an excess of receptors on the outside of tumor cells, doctors can give drugs to target them.

GRAPHIC BY JOHN MACNEILL; DATA FROM NATIONAL HUMAN GENOME RESEARCH INSTITUTE, WORLD HEALTH ORGANIZATION, FOUNDATION MEDICINE

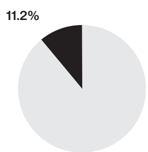
Baxter is the first of a new generation of industrial robots. Developed by Rethink Robotics, a company founded by robotics pioneer Rodney Brooks, it learns by demonstration. It's able to adapt to its environment and to the presence of humans.

facturing

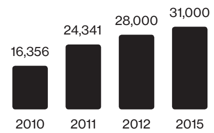
Smarter, safer robots could expand automation to new areas of production work and help many manufacturers regain a competitive edge against those using low-cost labor.

Photographs by Max Aguilera-Hellweg

Re-booting



Percent of U.S. GDP due to manufacturing sector



Projected and actual shipments of industrial robots in North America

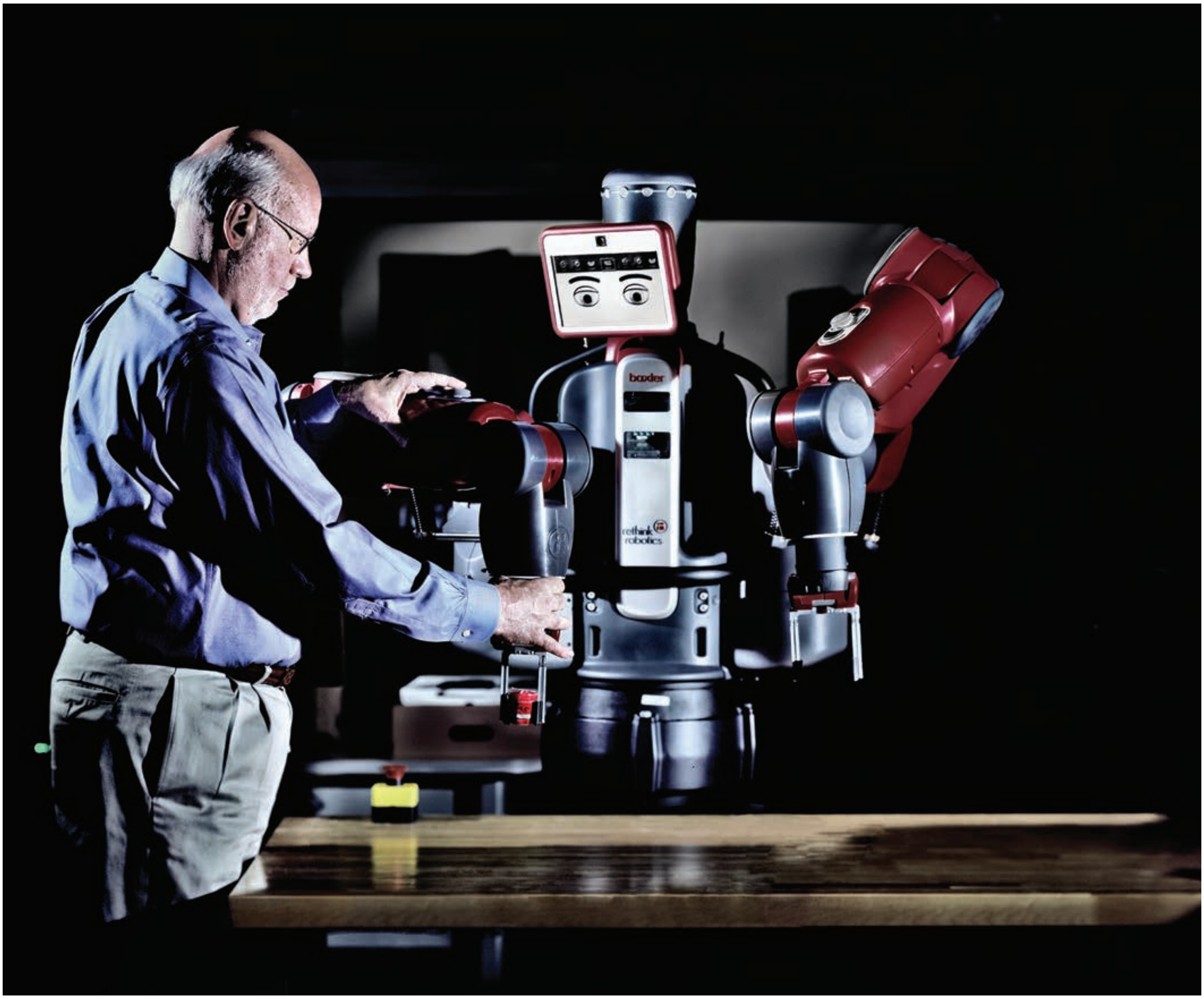
$8.5 billion

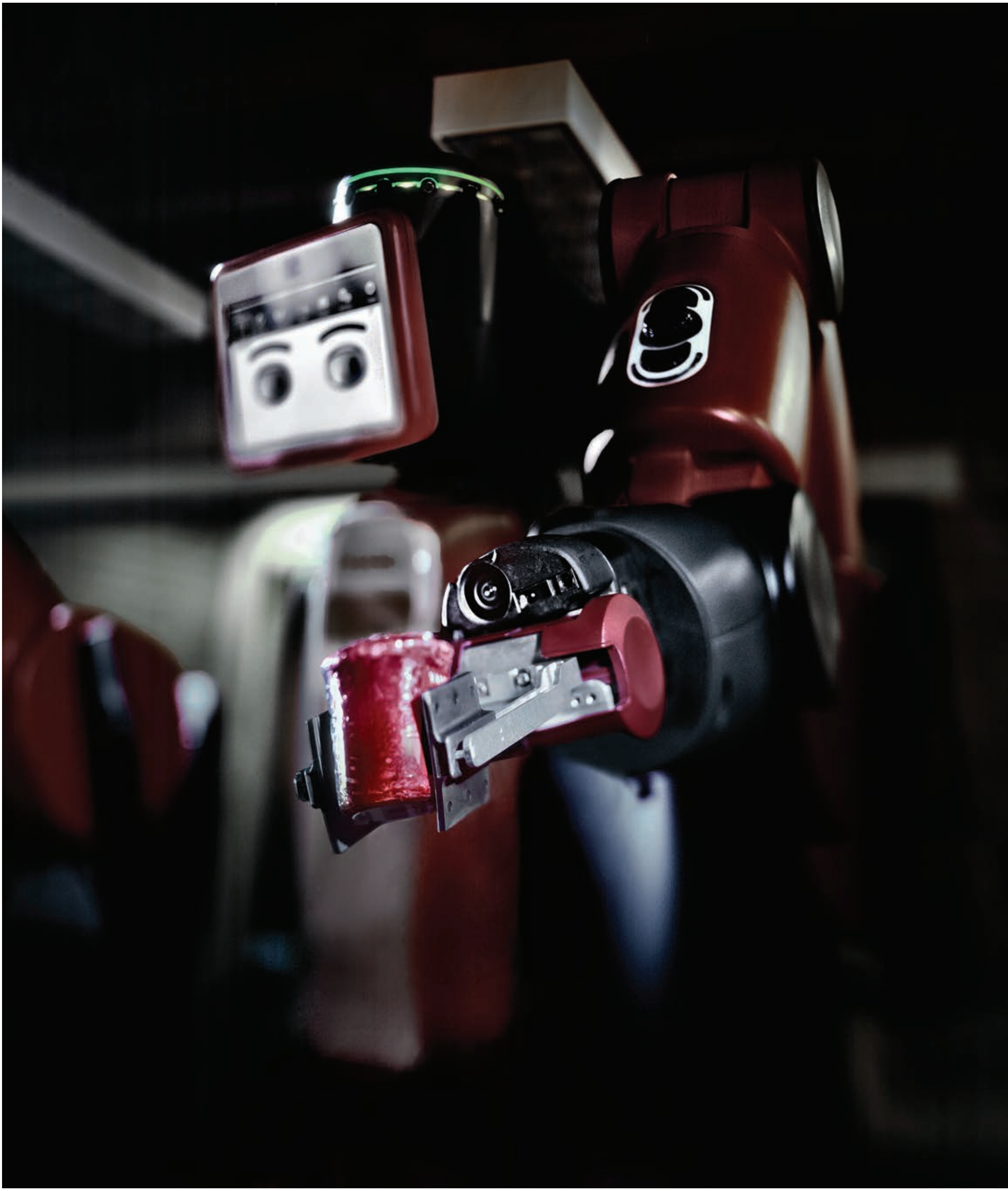
Worldwide market for industrial robots

Manu-facturing

DATA FROM BUREAU OF ECONOMIC ANALYSIS, INTERNATIONAL FEDERATION OF ROBOTICS

Robots like Baxter could bring automation to small-scale manufacturing for the first time, helping companies compete with those using low-cost human labor. Here, Mike Bugda, product manager for Rethink, "programs" the robot by showing it how to grasp an object from a conveyor belt. The robot uses the eyes on its screen to show where it will reach next.


baxter
rethink robotics



OPPOSITE: *Baxter is less precise and dexterous than a conventional factory robot. But it can be trained in only a few minutes by just about anyone, which could be vital to manufacturers that perform short production runs. The robot uses sensors to avoid human workers. Its arms, which move relatively slowly, will stop immediately if a collision does occur.*

ABOVE: *Interchangeable "hands" let Baxter perform a range of different tasks. A suction-cup grabber, for example, enables it to grasp unusual shapes. When you grab one of Baxter's arms, it feels light as a feather, its motors compensating for gravity in response to your touch so that the heavy limb is easy to move through the air.*

In August, NASA used a series of precise and daring maneuvers to put a one-ton robotic rover named *Curiosity* on Mars. A capsule containing the rover parachuted through the Martian atmosphere and then unfurled a "sky crane" that lowered *Curiosity* safely into place. It was a thrilling moment: here were people communicating with a large and sophisticated piece of equipment 150 million miles away as it began to carry out experiments that should enhance our understanding of whether the planet has or has ever had life. So when I visited NASA's Johnson Space Center in Houston a few days later, I expected to find people still basking in the afterglow. To be sure, the Houston center, where astronauts get directions from Mission Control, didn't play the leading role in *Curiosity*. That project was centered at the Jet Propulsion Laboratory, which Caltech manages for NASA in Pasadena. Nonetheless, the landing had been a remarkable event for the entire U.S. space program. And yet I found that Mars wasn't an entirely happy subject in Houston—especially among people who believe that humans, not only robots, should be exploring there.

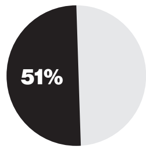
In his long but narrow office in the main building of the sprawling Houston center, Bret Drake has compiled an outline explaining how six astronauts could be sent on six-month flights to Mars and what they would do there for a year and a half before their six-month flights home. Drake, 51, has been thinking about this since 1988, when he began working on what he calls the "exploration beyond low Earth orbit dream." Back then, he expected that people would return to the moon in 2004 and be on the brink of traveling to Mars by now. That prospect soon got ruled out, but Drake

DATA FROM 2009 CBS NEWS POLL AND NASA

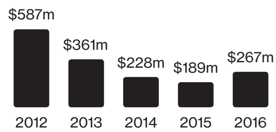
Years since a human has gone beyond Earth orbit

40

Percentage of Americans who favor sending astronauts to Mars



Obama administration's proposed budgets for Mars exploration



The Deferred Dreams of MARS

OFFICIALLY, THE UNITED STATES PLANS TO SEND ASTRONAUTS TO THE RED PLANET IN THE 2030s. IT'S NOT LOOKING LIKELY. BUT AT NASA, ENGINEERS LIKE BRET DRAKE KEEP PLUGGING AWAY.

By Brian Bergstein

Photographs by Brent Humphreys

Bret Drake in his office, which is lined with artists' conceptions of what astronauts might do on Mars.

pressed on: in the late 1990s he was crafting plans for human Mars missions that could take place around 2018. Today the official goal is for it to happen in the 2030s, but funding cuts have inhibited NASA's ability to develop many of the technologies that would be required. In fact, progress was halted entirely in 2008 when Congress, in an effort to impose frugality on NASA, prohibited it from using any money to further the human exploration of Mars. "Mars was a four-letter dirty word," laments Drake, who is deputy chief architect for NASA's human spaceflight architecture team. Even though that rule was rescinded after a year, Drake knows NASA could perpetually remain 20 years away from a manned Mars mission.

If putting men on the moon signified the extraordinary things that technology made possible in the middle of the 20th century, sending humans to Mars would be the 21st-century version. The flight would be much more arduous and isolating for the astronauts: whereas the Apollo crews who went to the moon were never more than three days from home and could still make out its familiar features, a Mars crew would see Earth shrink into just one of billions of twinkles in space. Once they landed, the astronauts would have to survive in a freezing, windswept world with unbreathable air and 38 percent of Earth's gravity. But if Drake is right, we can make this journey happen. He and other NASA engineers know what will be required, from a landing vehicle that could get humans through the Martian atmosphere to systems for feeding them, sheltering them, and shuttling them around once they're there.

The problem facing Drake and other advocates for human exploration of Mars is that the benefits are mostly intangible. Some of the justifications that have been floated—including the idea that people should colonize the planet to improve humanity's odds of survival—don't stand up to an economic analysis. Until we have actually tried to keep people alive there, permanent human settlements on Mars will remain a figment of science fiction.

A better argument is that exploring Mars might have scientific benefits, because basic questions about the planet remain unanswered. "We know Mars was once wet and warm," Drake says. "So did life ever arise there? If so, is it any different than life here on Earth? Where did it all go? What happened to Mars? Why did it become so cold and dry? How can we learn from that and what it may mean for Earth?" But right now *Curiosity* is exploring these very questions, firing lasers at rocks to determine their composition and hunting for signs of microbial life. Because of such robotic missions, our knowledge of Mars has improved so much in the past 15 years that it's become harder to make the case for sending humans. People are far more adaptable and ingenious than robots and surely would find things drones can't, but sending them would jack up the cost of a mission exponentially. "There's just no real way to justify human exploration solely on the basis of science," says Cynthia Phillips, a senior research scientist at the SETI Institute, which hunts for evidence of life elsewhere in the universe. "For the cost of sending one human to Mars, you could send an entire flotilla of robots."

Kennedy's objective was not to further science or even, really, to further space exploration. Going to the moon was a proxy for a nuclear strike on the Soviet Union. And it turned out to be a suboptimal way to build a space program for the long haul.

WHY IT MATTERS

Exploring for its own sake, even when there is no immediate, obvious benefit, is something humans have always done.

And yet human exploration of Mars has a powerful allure. No planet in our solar system is more like Earth. Our neighbor has rhythms we recognize as our own, with days slightly longer than 24 hours and polar ice caps that grow in the winter and shrink in the summer. Human explorers on Mars would profoundly expand the boundaries of human experience—providing, in the minds of many space advocates, an immeasurable benefit beyond science. "There have always been explorers in our society," says Phillips. "If space exploration is only robots, you lose something, and you lose something really valuable."

The Apollo Hangover

Mars was proposed as a place to explore even before the space program existed. In the 1950s, scientists such as Wernher von Braun (who had developed Nazi Germany's combat rockets and later oversaw work on missiles and rockets for the United States) argued in magazines and on TV that as space became mankind's next frontier, Mars would be an obvious point of interest. "Will man ever go to Mars?" von Braun wrote in *Collier's* magazine in 1954. "I am sure he will—but it will be a century or more before he's ready."

Von Braun and other space architects saw Mars as an end point in a stepwise approach to human space exploration—a formulation that influenced NASA's long-range plan in 1959, shortly after the agency was created. Under this framework, humans would first reach low Earth orbit. Then they would develop ships that could reliably go to and from orbit. A space station would follow. Next, sometime after 1970, people would land on the moon and, eventually, at an unspecified future date, on Mars. All the while, unmanned probes would explore the solar system as well. The underlying idea—that each step would provide expertise use-

Bruce Sauser, in front of a mockup of a space habitat, holds a sample of woven Kevlar strips that could cover an inflatable structure on Mars.

ful for the ones that followed—is "one of the great memes in the history of spaceflight," says Roger Launius, a former chief historian for NASA who is now senior curator in spaceflight at the Smithsonian Institution. "A whole lot of people bought into it."

The plan might have held, except that in 1961, when only the first step had been accomplished, President John F. Kennedy jumped over the next two and vowed to reach the moon by the end of the decade.

Kennedy's objective was not to further science or even, really, to further space exploration. Going to the moon was a proxy for a nuclear strike on the Soviet Union, a psychological tactic aimed at asserting American superiority. And it turned out to be a suboptimal way to build a space program for the long haul. An unsustainable level of resources went into reaching the moon—at its peak in the mid-1960s, NASA got $5 billion a year, more than 4 percent of the U.S. budget. (It gets about 0.5 percent now.) Even before Neil Armstrong and Buzz Aldrin bounced across the lunar surface in 1969, NASA's budgets and workforce were being slashed. "By casting Apollo as a race, there was no reason to continue once we won the race," says John Logsdon, founder of the Space Policy Institute at George Washington University.

NASA leadership suggested human exploration of Mars after the moon, but the Nixon administration scuttled the idea as too expensive. The president's economic advisor cited a poll, published in *Newsweek* magazine about two months after the moon landing, in which 56 percent of respondents said the government should reduce funding for space exploration. (In 1979, another poll would find that half of Americans felt landing men on the moon had not been worth it.) NASA continued its ambitious and successful program of exploring Mars and other planets with unmanned probes such as *Viking*, *Mariner*, and *Voyager*. But human exploration retreated to step two in NASA's original framework: the space shuttle would fly 135 times from 1981 through 2011. Next came step three, the International Space Station. By the time Bret Drake got his aerospace-engineering degree and began working as a contractor on shuttle missions in the mid-1980s, the idea of sending humans to Mars had essentially fallen off the radar.

Then in 1986, the *Challenger* exploded shortly after launch, killing all seven astronauts aboard. NASA suspended shuttle flights for two and a half years and was forced into a wrenching reassessment of its purpose. Commissions were appointed; manned exploration of the moon and Mars were once again suggested as long-term goals. And on July 20, 1989, the 20th anniversary of the first moon landing, President George H.W. Bush said the United States should strive for both places. "Like Columbus, we dream of distant shores we've not yet seen," he said. "Why the moon? Why Mars? Because it is humanity's destiny to strive, to seek, to find."

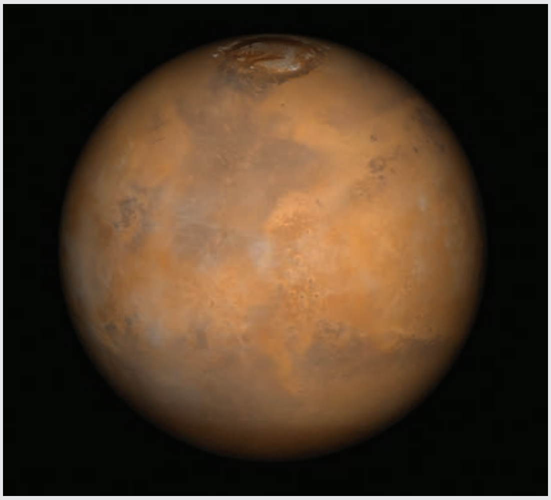
What Do You Eat?

Congress killed Bush's plan, at least partly because NASA estimated it would cost about $500 billion over 30 years. Bush's son, President George W. Bush, and his successor, Barack Obama, have since held up human exploration of Mars as a goal for NASA, but the funding necessary to make it happen hasn't followed during either administration.

All the while, Drake and his colleagues have plugged away, in fits and starts, at the long-term work required to keep the possibility open. Befitting a lifelong NASA employee, Drake lacks the wild-eyed bluster of space-colonization zealots. He is

The Imperative to Explore

By Buzz Aldrin



Mars, in a computer-enhanced composite of pictures taken by NASA's Mars Global Surveyor.

Following our first "small step for man" with the *Apollo 11* landing on the moon on July 20, 1969, there was an expectation that mankind was embarking on our ultimate journey—the expansion of humanity into the cosmos. Unfortunately, more than 43 years since that remarkable event, we have made little progress toward this larger goal, save for extended human presence in low Earth orbit. One might question the very premise of our undertaking such a journey in the first place.

As Neil and I first stood on the surface of the moon looking back at Earth—a bright blue marble suspended in the blackness of space—the experience moved us in ways that we could not have anticipated. We immediately realized just how precious our tiny planet truly was, knowing that everyone who had ever lived, all the knowledge that was ever discovered, everything we had ever known or loved, resided on that astonishingly beautiful, incredibly small planet we call our home.

Yet there was also a sense of connectedness. Earth is in space, and everything that formed our planet—the elements from distant stars that combined with other elements and found their way to this special crucible that produced life, our life—came from space. Given that, the very question of whether we should go into space seems moot. We are already in space. It surrounds us, provides the energy that ultimately feeds and sustains us, while tantalizing us with its mysteries and fueling our hunger for understanding—understanding our origins, the uniqueness or abundance of life in the universe, and our human destiny.

There are, of course, many practical reasons for us to explore. They touch on our economic strength, our health and well-being, and the ability of our planet, with its finite and limited resources, to sustain us.

In my own generation, NASA's Mercury, Gemini, and Apollo programs inspired countless young students to pursue degrees in science and engineering, creating a technical workforce unmatched in our history. Many of these students eventually contributed to Apollo, and to other space-related endeavors, while others went on to careers in other fields. In the collective, they produced the technological breakthroughs that led to our successes in space, but they also produced technologies and capabilities that are a part of our daily lives—instantaneous global communication, weather forecasts and disaster prediction, systems that let us observe tyrants and monitor treaty compliance (which helps ensure peace), and electronic devices held in our hands that seem only slightly removed from "magic," not to mention the analytical medical and health-care systems that extend our lives and contribute to our well-being. This remarkable growth in engineering, technology, and science created an economic base that still sustains us.

One of the most important questions we need to face in the near term is the question of sustainability. A world population of more than seven billion people is growing rapidly, consuming the limited resources of our planet at an unsustainable rate while we also create environmental distress that may adversely affect our future viability on Earth. We now have a clear choice—to compete for the diminishing resources remaining on Earth (a closed system) or to coöperate in the exploitation of the limitless resources and opportunities evident in space (an open and expansive system). To me the choice is an obvious one.

Given the periodicity of global events that have threatened life on Earth, and the inevitability of many new threats that we cannot predict, there is one obvious step we can undertake to enhance the survivability of our species, as our forefathers did so many years ago. That is to explore and settle new worlds, thereby establishing dissimilar redundancy and new populations that will doubtless evolve in very diverse ways, much as humanity did in the different continents on which it established a foothold and a new beginning here on Earth.

Former astronaut Buzz Aldrin has spent decades developing his idea for the Aldrin Mars Cycler, a reusable system for transferring people and cargo from Earth to Mars.

plainspoken and reserved, even when he acknowledges his frustration over the endless studies his group has had to perform in the absence of an actual Mars mission. "We know what the challenges are," he says. "We know what technologies, we know what systems we need."

The challenges are mind-boggling. That's abundantly clear from the mission outline, officially called a "design reference architecture," that he completed in 2009. Going into space for more than two years would subject the astronauts to an unprecedented degree of isolation and extended weightlessness; the longest stay in space so far has been 14 months. Potentially deadly cosmic rays, which are blocked by Earth's magnetic field and atmosphere, would hit the spacecraft in flight and threaten the astronauts on Mars. NASA could reduce exposure to the normal background radiation in space by building shielding into the spacecraft and the Martian habitats. But it probably needs a better method of predicting occasional solar flares that spew higher doses of radiation, so that astronauts could be sure to retreat to special "storm shelters."

Another unsolved problem is that the Martian atmosphere is thick enough for a landing vehicle to need thermal protection against the friction it would generate on entry, but it's also too thin to substantially slow such a craft down. That means a novel descent vehicle would be required: the sky crane used to land *Curiosity* wouldn't work for landing humans, whose craft could weigh 30 times more. Although NASA is building a heavy-lift vehicle that could take humans to Mars—essentially a bigger version of the rockets that flew to the moon—a lander is not yet in the works. Drake says development and testing of technologies for a lander must start in the next few years if a mission in the mid-2030s is to be possible.

All that is daunting, but the rocketry is at the heart of what NASA has done before. A much bigger challenge would come from having to do something entirely new: protect and feed humans on another planet over a long stretch. Astronauts spending extended periods on Mars would need to take off their space suits and helmets and breathe inside an enclosed structure. There are reasons to be optimistic; the space station has offered important lessons on building and maintaining "closed loop" life-support systems in which water and air are recycled. It's also possible to extract oxygen from the carbon dioxide that makes up 95 percent of the Martian air.

But basic problems remain, such as figuring out what the travelers would eat. A Mars habitat might have a greenhouse, but it's unlikely that astronauts could grow enough to meet all their caloric needs. And NASA food scientist Michele Perchonok doesn't believe the dehydrated food that astronauts inject with water on the space station can retain adequate nutrients for five years—which is how long it will have to last if some is sent ahead of the first crew, as envisioned. Many solutions are nonstarters because a rocket to Mars would be able to carry only so much weight in food and cooking equipment. Pressure-treating the food is probably the answer, but perfecting that method is hard. When I mentioned to Perchonok that a Mars mission was surely more than 20 years away, she laughed. "I hope so," she said. "Because we've got a lot of work to do."

In another building, Bruce Sauser—who has been at NASA as long as Drake—is overseeing several projects that could be used on Mars. One of them is a habitat that could withstand the vagaries of a planet where temperatures range from −140 °C to 25 °C and windstorms pound the landscape with dust. Sauser (who has a classic title: manager of the systems architecture and integration office of the engineering directorate) is trying to master a mix of materials for the habitat. Some layers would provide insulation and radiation shielding, for example, while others would be tough enough to stave off punctures. In turn, these layers would fit over bladders to hold in air. One idea is to make the habitat inflatable, so it could be packed tightly en route to Mars.

Sauser estimates it could take 10 to 15 years to be sure of this habitat's reliability. His team has experimented with materials such as Kevlar and Nextel, an insulator used on the shuttles. But he says that funding cuts and freezes have made it nearly impossible to make more than incremental progress.

"The dollars are spread across so many things, you don't have enough in any one bucket to take that thing to the next level," he says. "We don't have a mission. We don't have an end goal. If I don't have that real need, funding, or deadline, I'm going to keep putzing around with it. Well, putzing around can take 30 years."

"People who are not part of NASA or not part of the space community—maybe they're well informed, but they don't see practical applications in their daily lives. And they just have to scratch their heads and wonder: why are we doing this?"

The Right Stuff

Solving such problems, Drake says, wouldn't require as much money as you might think. He says a panel appointed by the Obama administration, the Augustine Commission, got it about right when it determined in 2009 that NASA could sustain programs for having both humans and robots explore Mars if its annual budget were boosted by about $3 billion over its 2010 level of $19 billion.

However, NASA's budget is going in the opposite direction (it's now under $18 billion), and the cuts are not just a reflec-

OPPOSITE: NASA/JPL/MSSS

tion of Washington's financial woes. They also reflect the ambivalence the public feels about what NASA achieves. On the most practical level, the best scientific research from human missions, from the 1970s Skylab space station through the shuttle and the International Space Station, has had to do with the bone loss, blurry vision, and other problems astronauts suffer when removed from Earth's gravity. This is crucial research if our species is to have a future in space. But it has the ring of circular logic: we must keep sending people into space so we understand what happens to people in space. "People who are not part of NASA or not part of the space community—maybe they're well informed, but they don't see practical applications in their daily lives," says Launius, the former NASA historian. "And they just have to scratch their heads and wonder: why are we doing this at the costs that we are?"

The question then becomes how much we should value the intrinsic benefits of spaceflight as an expression of our desire to explore our world in the most ambitious way possible.

Stan Love has a PhD in astronomy and has worked on dozens of projects for NASA, but the one-word title on his business card sums him up best: "astronaut." He flew to the space station on the shuttle *Atlantis* in 2008 and did two spacewalks. He says the argument for human space missions should be simple: "Exploring is one of the best things people do. Explorations that aren't easy inspire us. We learn new things. Often the things we learn seem to be worthless at the time."

Why not do it solely with robots? "We like it, as people, when people do things. If all you're after is science data—sure, send robots. But we as human beings feel an attachment when humans go and do things like this."

Love adds that even in the absence of an obvious economic reason to do it, the cost of an inspiring exploration would be worth bearing. The price would be small, he says, compared with the money and effort that get spent in the service of "greed and our ancestral urge to beat the crap out of each other."

One easy answer might be to say that if people want to go to Mars, then they should plan it and pay for it themselves. Indeed, several companies are proving they can do things in space relatively efficiently. One of them is Space Exploration Technologies, or SpaceX, a private company that is sending rockets to the space station for NASA. SpaceX's founder, Elon Musk, dreams of going to Mars. He says he wants to put people there in 12 to 15 years.

However, that goal seems to dramatically underestimate the technological obstacles. SpaceX is working on a heavy-lift rocket that could take robotic payloads to Mars. But humans require a bigger and more expensive rocket, and Musk has not revealed plans to build one. Even more important, he has not said how he would carry out the other difficult tasks, like nourishing the travelers (through a spokeswoman, he declined to comment). And even if such a private effort were able to invent and develop the needed technology, the logistics of Mars travel are so difficult that the costs would surely be too high to be covered solely by a new market in space tourism. In other words, it would demand the involvement of large institutions with financial and technical wherewithal—such as a space agency or a coalition of several.

The problem then remains: convincing the public that it is a worthwhile goal. Even within NASA there is no consensus. Brent Sherwood, who formulates solar-system missions for NASA at the Jet Propulsion Laboratory, contends that given the agency's funding constraints, the resources used to get people to Mars would be much better spent on other human space endeavors. Among other things, he advocates colonizing the moon, stimulating space tourism, and harvesting solar energy from geosynchronous Earth orbit. "I'm a space architect. I'd like to see us do amazing things in space," Sherwood says. "I just don't believe that the only measure of amazingness is half a dozen civil servants visiting Mars in 40 years."

Sherwood, 54, got into the spaceflight business in 1988, when he worked for Boeing on planning human Mars missions. He considers Drake an old friend; he points out that like many people their age, both were inspired by Apollo to join the space program. But he thinks the Apollo legend looms too large, leading people to suggest Mars as the natural successor to the moon when, in fact, the moon landings were anomalies of the Cold War. "Bret has been at it for all those years. I've watched us grow old," Sherwood marvels. "I think it's particularly elegiac that the generation that was motivated to get into this business because of Apollo is trapped in a limited and limiting and sort of quaint vision of what we thought we're here to do."

Why not explore Mars and space solely with robots? "We like it, as people, when people do things. If all you're after is science data—sure, send robots. But we as human beings feel an attachment when humans go and do things like this."

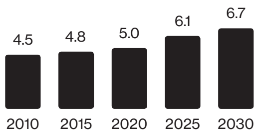
What is NASA really here to do? It's a question that hasn't been adequately answered in 40 years—not by politicians, space experts, or the agency itself. In the meantime, Bret Drake and his colleagues do what they can to keep a flame alive, just in case our society decides that we really want to do something fundamental and magnificent simply because we can. T

Brian Bergstein is the deputy editor of MIT Technology Review.

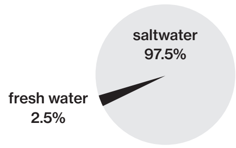
SOLUTIONS • WATER

Nanopore Desalination

Projected global water demand (in trillion cubic meters)

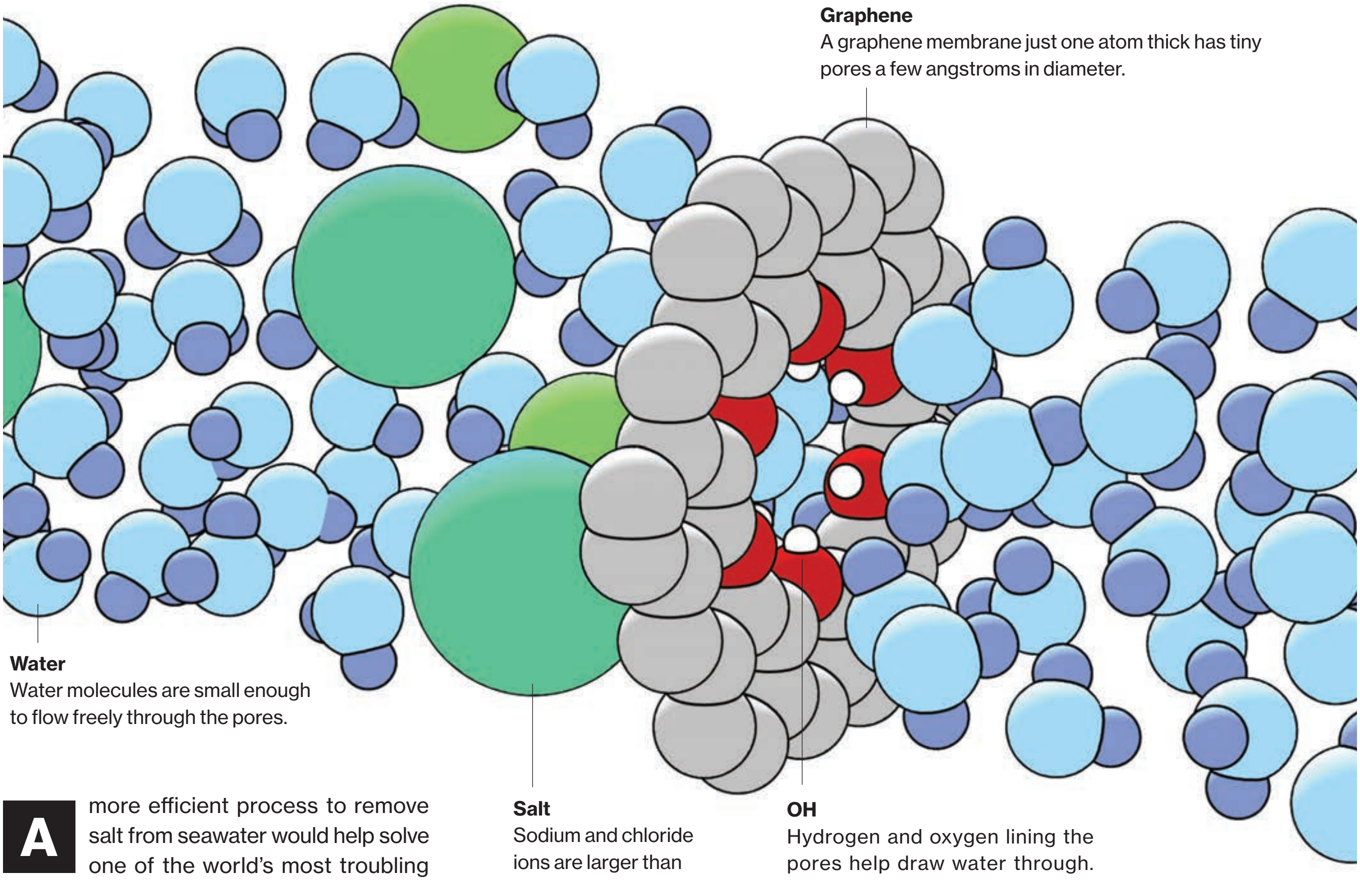


Total world water



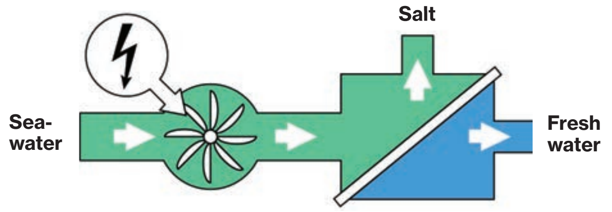
Number of people without access to improved water sources

894 million



A more efficient process to remove salt from seawater would help solve one of the world's most troubling problems: limited access to clean water. Most commercial desalination is based on reverse osmosis, in which pressure differences drive water through a membrane that is impermeable to salt. But the process is energy-intensive (because of the power needed to create the pressure gradient) and slow. MIT researchers led by David Cohen-Tanugi and Jeffrey C. Grossman envision an alternative based on graphene dotted with holes too small for salt to pass through. Because the system requires much less pressure, it could be cheaper; and because water flows freely through the pores, it could be far faster.

Reverse osmosis



In conventional desalination, an electric motor is used to create a pressure gradient, pushing water through a semipermeable membrane.

GRAPHIC BY JOHN MACNEILL; DATA FROM THE UNITED NATIONS; EUROPEAN ENVIRONMENT AGENCY

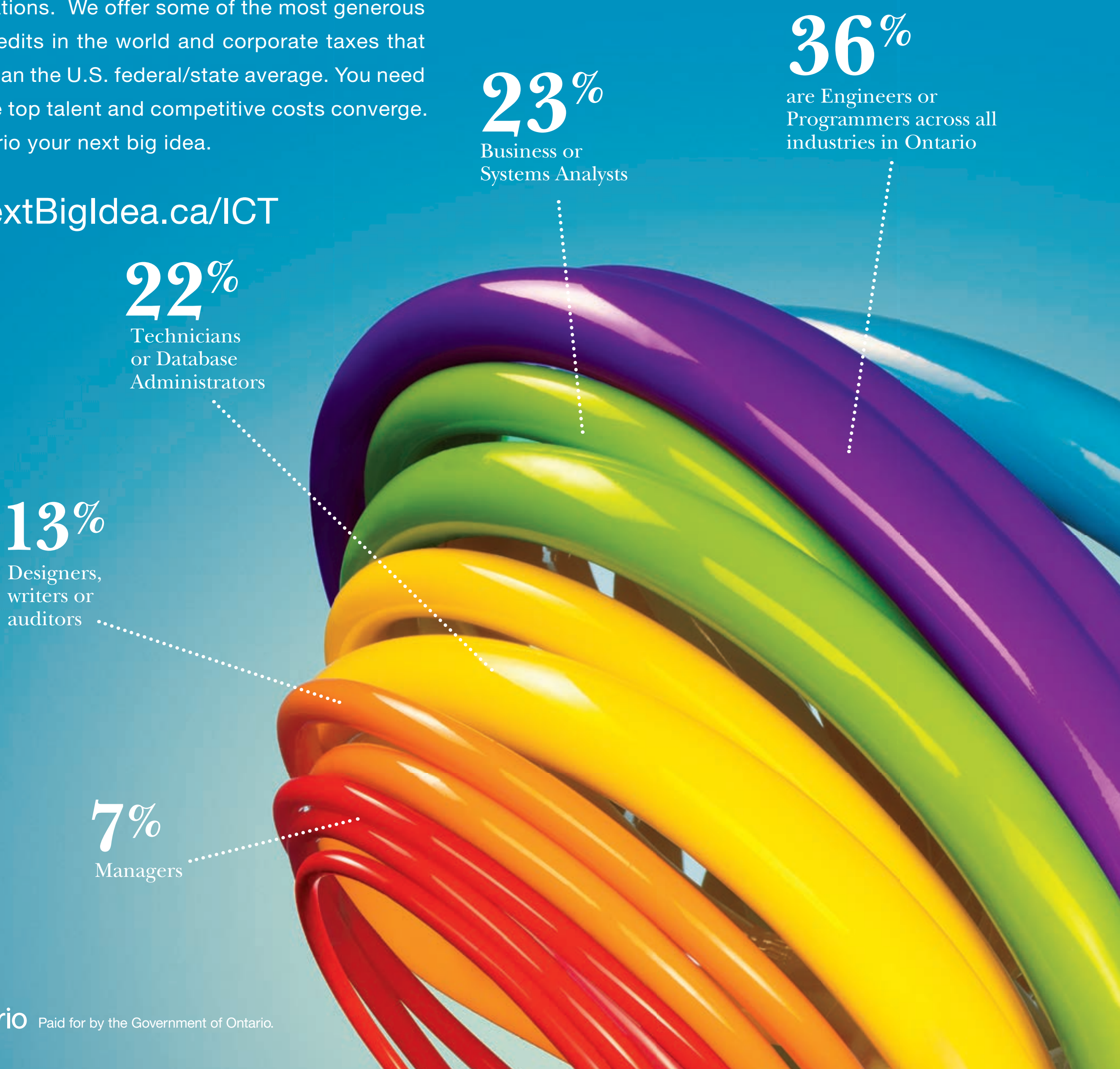
HERE'S WHY ONTARIO, CANADA

IS YOUR NEXT BIG IDEA

ONTARIO
CANADA

Innovation is at the core of the information and communications technology industry in Ontario, Canada. Our diversified talent pool of more than 300,000 skilled ICT workers – close to 60% of whom are post-secondary graduates – working with world leading infrastructure and communications networks means invention and commercialization come easy in Ontario. Ontario is home to industry giants and small start ups alike with strengths in areas that include digital gaming, mobile app development and wireless communications. We offer some of the most generous R&D tax credits in the world and corporate taxes that are lower than the U.S. federal/state average. You need to be where top talent and competitive costs converge. Make Ontario your next big idea.

YourNextBigIdea.ca/ICT



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A BUSINESS REPORT ON

Innovation Funding

Venture capital is losing its impact. So what's next? In this report, *MIT Technology Review* charts whether prizes, outsourcing, and citizen crowds can unlock the next explosion of innovation.

Read all 12 stories in this report at technologyreview.com/business

Additional stories include: *What Technology Will Be Crowdfunded?*, *Innovation in Manufacturing Takes a Village, The Impresario Who Sells Prizes*, and more.

OLIVER MUNDAY

THE BIG QUESTION

Money Seeks Idea

Businesses are adapting their R&D spending to the idea that innovation can come from anywhere.

● Where does innovation come from? For one answer, consider the work of MIT professor Eric von Hippel, who has calculated that every year U.S. consumers spend $20 billion in time and money trying to improve on household products—for example, modifying a dog-food bowl so it doesn't slide on the floor. Von Hippel estimates that these backyard Edisons collectively invest more in their efforts than the largest corporation anywhere does in R&D.

The low-tech kludges of consumers might once have had little impact. But one company, Procter & Gamble, has actually found a way to tap into them; it now gets many of its ideas for new Swiffers and toothpaste tubes from the general public. One way it has managed to do so is with the help of InnoCentive, a company in Waltham, Massachusetts, that specializes in organizing prize competitions →

over the Internet. Volunteer "solvers" can try to earn $500 to $1 million by coming up with answers to a company's problems.

We like Procter & Gamble's story because the company has discovered creative, systematic ways to pay for ideas originating far outside its own development labs. It's made an innovation in funding innovation, which is the subject of this business report.

How we pay for innovation is a question prompted, in part, by the beleaguered state of the venture capital industry. Over the long term, it's the system that's most often gotten the economic incentives right. Consider that although fewer than two of every 1,000 new American businesses are venture backed, these account for 11 percent of public companies and 6 percent of U.S. employment, according to Harvard Business School professor Josh Lerner. (Many of those companies, although not all, have succeeded because they've brought new technology to market.)

Yet losses since the dot-com boom in the late 1990s have taken a toll. In August, the nation's largest public pension fund, the California Public Employees Retirement System, said it would basically stop investing with the state's venture funds, citing returns of 0.0 percent over a decade.

The crisis has to do partly with the size of venture funds—$1 billion isn't uncommon. That means they need big money plays at a time when entrepreneurs are headed on exactly the opposite course. On the Web, it's never been cheaper to start a company. You can outsource software development, rent a thousand servers, and order hardware designs from China. That is significant because company founders can often get the money they need from seed accelerators, angel investors, or Internet-based funding mechanisms such as Kickstarter.

"We're in a period of incredible change in how you fund innovation, especially entrepreneurial innovation," says Ethan Mollick, a professor of management science at the Wharton School. He sees what's happening as a kind of democratization—the bets are getting smaller, but also more spread out and numerous. He thinks this could be a good thing. "One of the ways we get more innovation is by taking more draws," he says.

In an example of the changes ahead, Mollick cites plans by the U.S. Securities and Exchange Commission to allow "crowdfunding"—it will let companies raise $1 million or so directly from the public, every year, over the Internet. (This activity had previously been outlawed as a hazard to gullible investors.) Crowdfunding may lead to a major upset in the way inventions get financed—especially those with popular appeal and modest funding requirements, like new gadget designs.

Citizen crowds have far less to offer in capital-intensive domains such as manufacturing, pharmaceuticals, and energy. Innovation in these sectors requires investments in the tens and hundreds of millions of dollars. What's more, the payoff time is more often measured in decades than in months. Yet R&D funding in these industries is also in transition. Manufacturers, for example, are pooling resources with government help to try to gain an R&D edge in newer areas such as 3-D printing.

So what's at stake in all this? The case of the pharmaceutical industry is instructive. In 2010, half of the top 10 corporate R&D spenders, including all of the top three, were drug firms. Yet despite huge budgets (in some cases $9 billion annually), the industry is famished for new products. It simply can't get its R&D to pay off.

Last year, the head of strategy for drug maker GlaxoSmithKline warned that if the innovation problem isn't fixed, this might mark "the last generation of R&D spending" for large drug firms. The giant pharmaceutical research divisions, in other words, are in danger of getting cut back and broken up.

The drug industry's answer is also to try to decentralize its spending. Glaxo is pushing nearly half its R&D dollars into the hands of academics and biotech companies, hoping they have the insight or intuitions it doesn't. Other drug companies are doing the same. Because of the scale of pharmaceutical research spending, the shift is taking years. Given the importance of drug research to human well-being, we should all hope they find the innovations they're looking for. *—Antonio Regalado*

LEADERS

The Narrowing Ambitions of Venture Capital

Venture capital was supposed to be the financial engine of American innovation. Instead, it's become a reflection of its own limitations, says Josh Lerner.

NEAL HAMBERG

Josh Lerner

● This election year, Republicans and Democrats will agree on little, including how to get the U.S. economy growing. Higher taxes or smaller government? One path to growth that is widely agreed upon is technological innovation, which has historically been closely associated with the American venture-capital-backed startup company.

A single dollar of venture capital, one study suggests, is as effective at boosting new ideas as three dollars of corporate investment in R&D. If we listened to trade bodies such as the National Venture Capital Association, we might conclude that to get more innovation, all we need is more

venture capital. But claims that venture capital is a driver of true innovation, or even of positive financial returns to investors, face some hard questions. With the industry facing a hangover from its recent flurry of social-media investing and the disappointing stock market performance of firms such as Groupon, Zynga, and Facebook, the skeptics have rarely been as loud as they are today.

I believe several essential constraints limit venture capitalists' ability to promote true innovation. The first is that venture investors have financed a progressively narrower range of technologies. Recently, a few hot areas—most notably Web and social media—have dominated an increasingly large share of the venture landscape. While another smartphone app to identify the drinking establishment where your buddies are currently carousing may benefit fraternity and sorority members, it is hard to feel that such ventures address fundamental challenges facing mankind today.

Investor Peter Thiel has aptly expressed the core anxiety: "We wanted flying cars. Instead we got 140 characters."

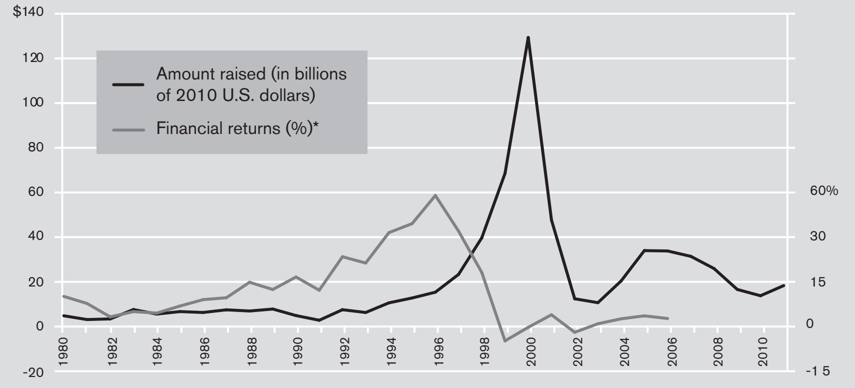
Historical data bear out the trend. In 1974, the fraction of venture capital investments primarily involving computers and telecommunications was only 35 percent, a share that climbed to 62 percent in 1982 (as excitement grew around computer peripherals) and finally reached 79 percent during the dot-com boom in 2000 before subsiding temporarily. The figure has rapidly climbed again, reaching 56 percent in 2011. And that may yet mask the rise of social-media investing, which fits poorly into traditional classification schemes.

What explains this dramatic concentration? One answer is that venture funds have done much better in categories where the innovation cycle is short, such as media and software, than in areas like advanced materials and biotechnology, where the time frame for success is longer than the eight-to-10-year life of the typical fund.

Estimates assembled by the consulting firm Sand Hill Econometrics show that a dollar invested in 1991 in venture-backed software firms would have turned →

Feast, Then Famine

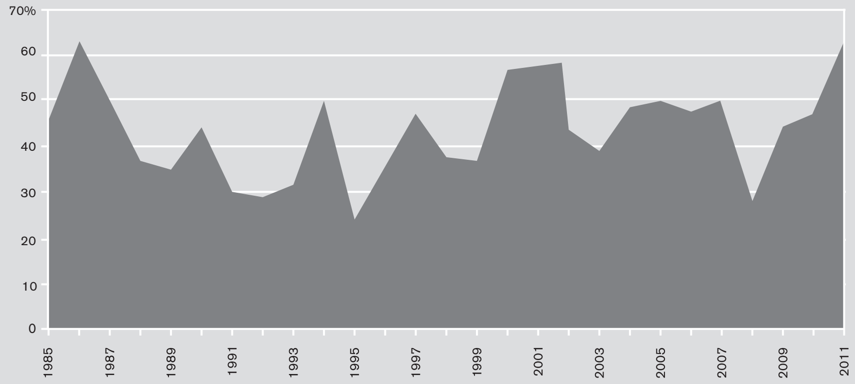
Fund-raising and investment returns of U.S. venture capital firms follow a boom-and-bust cycle.



*Capital-weighted average internal rate of return for the given fund-raising year.
Source: Thomson Reuters

An Uneven Appetite for Risk

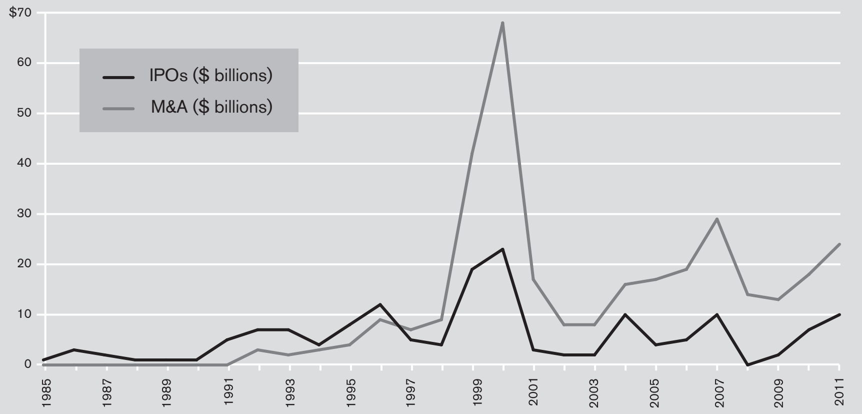
Investors swing between exuberance and caution in this risk-taking index. Data show money allocated to seed and early-stage companies as a share of total venture capital investments.



Source: NVCA Yearbook

Heading for the Exits

Venture investors recoup their money by taking companies public in IPOs, or by selling them in a merger or acquisition. Values of deals for U.S. venture-backed companies are shown.



Source: NVCA Yearbook

into more than $23 by the end of 2011, for an annual return of close to 19 percent. Investments in health care and retail had an annual return of 10 percent over this period, while a similar investment in the bedraggled "other" category—which includes energy and transportation—returned only 6 percent. Once the venture capitalists' annual fees (which typically run about 2 percent of the capital under management) and profit share (20 percent or more of the capital gains) are factored in, the performance difference would be even larger.

Claims that venture capital is a driver of true innovation, or even of positive financial returns to investors, face some hard questions.

The apparently limited power of the venture capitalists' "pixie dust" only serves to concentrate their efforts further. Groups specializing in computers and telecommunications have had superior returns, which has allowed them to garner more money. Others struggle, disappear, or reinvent themselves as mainstream investors in popular categories.

A second critical limitation is that the venture market is extraordinarily uneven, moving from feast to famine and back again. Consider the tremendous surge in funding for biofuels, which peaked in 2006, and again in social-media companies during the last two years. During booms, unjustified exuberance rules. A common phenomenon is known as "money chasing deals." As more money flows into funds from institutional and individual investors, venture capitalists are willing to invest in ever riskier deals (and often on worse terms): the share of first-round venture dollars going to seed-stage companies—those whose prospects are least certain—ranged from 24 percent in 1995 to 58 percent in 2000–'01 before reaching a high of 61 percent in 2011. This risk-taking is not rewarded: returns in boom years such as 2000 are among the lowest seen in any period.

Cycles in the venture industry stem largely from the behavior of funds themselves. During hot markets, inexperienced groups raise capital, often from unseasoned investors who are attracted by the excitement—not appreciating that first-time funds often show weaker performance, particularly in hot markets.

Name-brand groups, too, often take advantage of exuberant markets to raise money aggressively, perhaps because partners' compensation is driven by fees on capital under management. As venture groups grow, they increase the capital that each partner is responsible for and broaden the range of industries in which each invests. In other words, what starts as a trickle ends as a torrent. Ultimately the expansion proves unsustainable as investment returns fall. Then the cycle repeats itself all over again.

Whatever the precise mechanisms behind the boom-and-bust cycle, its impact on innovation is worrisome. For instance, during the deep venture trough of the 1970s—no venture capital funds at all were raised in the United States in 1975—many companies that sought to pioneer personal computing languished unfunded. Ultimately, these technologies surfaced with revolutionary impact in the 1980s, but their emergence might have been accelerated had the venture market not been in such a deep funk. It is hard not to feel that many long-term, expensive investment areas, such as clean tech, manufacturing, and biotech, are in exactly such a trough today.

The overfunding of startup firms during booms carries its own negatives. Examples include the frenzy surrounding B2B and B2C Internet companies in the late 1990s. The result is waste: multiple companies pursue the same opportunity, each often more marginal than the last. The initial market leader's staff is poached by the me-too followers, disrupting the progress of the firm with the best chance of success.

So when do booms turn to busts? Venture capitalists depend critically on acquisitions and the public stock markets to help them exit their investments and return capital to their investors. But the public markets are fickle. During the past decade, soaring enthusiasm—for clean tech in 2006–'07 and social media in 2010–'12—each time abruptly subsided, leaving the portfolios of venture capitalists, and stock investors, in shambles.

Ironically, busts may promote innovation precisely because they frustrate venture capitalists' efforts to exit their investments. According to the latest academic research, venture-backed companies that consider going public but abandon the efforts in the face of unfavorable market conditions are actually more innovative.

Senior partners at an established venture firm are likely to have a pretty sanguine view of their own (and their partners') ability to effect positive change in the firms they fund and in society at large. This is understandable: one is unlikely to be successful at committing skittish institutions' money to nascent startups without a considerable degree of self-confidence.

But the venture capital model is no panacea for innovation. The boom-and-bust cycle, the mercurial effects of public markets, and the narrowing of its objectives have made it something far less substantial.

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CASE STUDIES

Singapore Seeks a Breakthrough to Call Its Own

The Asian nation has spent billions on R&D and lured technology superstars. So why does it lag in innovation?

● The software that entrepreneur Terence Swee ships around the world was developed in Singapore, but you would never know it.

His company, Muvee Technologies, which creates software that automati-

A view of Fusionopolis, Singapore's newest technology park.

FLICKR CREATIVE COMMONS

cally edits videos to the beat of a music soundtrack, is vague about the exact address of its headquarters. It uses American English in its ads and holds sales on Thanksgiving rather than Chinese New Year. Its office is retrofitted with a 1950s-style American diner. "We don't explicitly state that we are from Singapore," Swee says. "The world is still more comfortable buying software from the USA."

Singapore is known for being hospitable to innovation. But underneath the success lurks an identity crisis: it has never had a blockbuster invention or technology it can call its own.

That's a stain on what's otherwise a Cinderella story of how a small island—less than half the size of London—transformed itself from a colonial backwater into one of the world's most affluent, most fully wired places in half a century. That rise is attributed to luck and smart planning by a government that has plowed billions into infrastructure, R&D subsidies, and tax breaks to lure multinational corporations. Yet Singapore's own ideas and startup companies are struggling to define themselves in the shadow of big names that have set up shop on its shores, such as Google, Hewlett-Packard, and Procter & Gamble. There's no company that jumps out as a Singaporean success in the same way that South Korea's Samsung or Japan's Sony does. Despite heavy investment in biomedical research, there's still no Nobel Prize, either. The country's most famous entrepreneur may actually be Eduardo Saverin, the Facebook cofounder who renounced his U.S. citizenship and took up residence in a Singapore penthouse.

That there's no distinctly Singaporean brand of innovation looks to some like an unintended consequence of too much government stimulation. Business leaders now publicly wonder whether Singapore's top-down approach, its obsession with standardized tests, and its law-and-order ways (bubble-gum sales are banned) are leading to a society that can produce no truly significant new ideas.

Such cultural clichés, however, fail to touch on the most important of Singapore's economic realities: the country's tiny size. That, say entrepreneurs and government officials, means Singapore must cater to global standards and markets or doom its businesses to irrelevance. In other words, the very same pragmatism that put Singapore on the international map may now explain why it doesn't stand out.

"It makes no sense to attempt a Yelp or a GrubHub for Singapore—the scale is just too small," says Darius Cheung, a 31-year-old who sold a mobile security company, tenCube, to McAfee in 2010. "So startups are forced to choose other kinds of innovation that can achieve larger scale across borders, such as something that is truly culture- and location-agnostic." Cheung's most recent venture, an English-language phone app called BillPin, lets friends track shared expenses like rent bills. It's the kind of thing that could get big, but only if it tops similar apps being written in San Francisco, New York, or London.

Singapore's economic takeoff began in the 1960s after the country gained independence. Attractive for its multiculturalism and its open-door banking policies, it added government incentives for aerospace and biomedical research. It has designated $12.9 billion to fund R&D from 2010 through 2015.

"Whenever one of my corporate clients around the world is thinking about establishing a new research hub in Asia, Singapore is always on the shortlist," says Andrew Taylor, a managing director at the Boston Consulting Group who coauthored a 2010 study that ranked Singapore as the most "innovation friendly" country in the world, ahead of the United States and Israel.

But in terms of actual innovation—output of ideas—the record is more mixed. While Singapore has become influential in some scientific fields, much of the activity is not driven by Singaporean companies. Foreign companies such as Hewlett-Packard and Micron Technology account for 15 of the top 20 patent filers in Singapore, and for over half of all intellectual-property claims, according to the National University of Singapore. That is much higher than the proportion seen in Japan, Korea, or Taiwan. The presence of →

multinationals has also acted as a disincentive to would-be entrepreneurs, who find it hard to turn down a high-status office job with an American-sized salary. Swee, the video editing entrepreneur, admits he's a bit unusual for politely refusing the overtures of headhunters. "There are so many people who could have formed the next generation of tech innovators but decided to take on managerial jobs in regional sales offices of the multinational corporations," he says.

Singapore has lately been trying to give more encouragement to its nascent entrepreneurial class. As part of a plan to double the number of local companies with at least $80 million in revenue by 2020, aiming for a total of 1,000, it is offering a mix of direct financing, grants, and state-run venture capital. "Singapore is a small country," Teo Ser Luck, minister of state for trade and industry, said in a speech this August. He thinks smaller companies "must think global at an early stage if they want to grow." Similarly, the government's current priority for biomedical startups is to fund those that have "scalability for the global market," an agency website says.

Some say that in setting global goals Singapore is missing the chance to formulate its own distinctive type of innovation—one aimed more narrowly, perhaps within Asia. "The key to developing innovation is plugging into the ecosystem and networks around us, but we haven't fully exploited our natural connections to the regional backyard," says Wong Poh Kam, director of the National University of Singapore Entrepreneurship Center.

The government has typically placed bets with name-brand U.S. universities. For example, Singapore-Stanford Biodesign, a collaboration with Stanford University, trains innovators in medical technology. But Singapore hasn't formed such partnerships with Universitas Indonesia or the University of the Philippines. Those untapped, underdeveloped markets could be the real opportunity for disruptive technology, Wong thinks. He blames the oversight on the "cultural attitudes of strategic planners," which he says "are colored by where they have been schooled—namely, places such as Harvard and MIT."

For Singapore's technology entrepreneurs, at least, the lack of a blockbuster Singaporean invention or product isn't any reason not to keep thinking globally. Just the opposite, says Swee, whose company now has 60 employees. "If you cannot compete with the best in the world," he says, "you shouldn't exist." *—Dawn Lim*

LEADERS

Software's Wealthiest Should Fund Innovation

Former Microsoft chief technology officer Nathan Myhrvold explains why he's backing the nuclear energy startup TerraPower.

OLIVER MUNDAY

● For some technologists, it's enough to build something that makes them financially successful. They retire happily. Others stay with the company they founded for years and years, enthralled with the platform it gives them. Think how different the work Steve Jobs did at Apple in 2010 was from the innovative ride he took in the 1970s.

A different kind of challenge is to start something new. Once you've made it, a new venture carries some disadvantages. It will be smaller than your last company, and more frustrating. Startups require a level of commitment not everyone is ready for after tasting success. On the other hand, there's no better time than that to be an entrepreneur. You're not gambling your family's entire future on what happens next. That is why many accomplished technologists are out in the trenches, leading and funding startups in unprecedented areas.

Jeff Bezos has Blue Origin, a company that builds spaceships. Elon Musk has Tesla, an electric-car company, and SpaceX, another rocket-ship company. Bill Gates took on big challenges in the developing world—combating malaria, HIV, and poverty. He is also funding inventive new companies at the cutting edge of technology. I'm involved in some of them, including TerraPower, which we formed to commercialize a promising new kind of nuclear reactor.

There are few technologies more daunting to inventors (and investors) than nuclear power. On top of the logistics, science, and engineering, you have to deal with the regulations and politics. In the 1970s, much of the world became afraid of nuclear energy, and last year's events in Fukushima haven't exactly assuaged those fears.

So why would any rational group of people create a nuclear power company? Part of the reason is that Bill and I have been primed to think long-term. We have the experience and resources to look for game-changing ideas—and the confidence to act when we think we've found one. Other technologists who fund ambitious projects have similar motivations. Elon Musk and Jeff Bezos are literally reaching for the stars because they believe NASA and its traditional suppliers can't innovate at the same rate they can.

In the next few decades, we need more technology leaders to reach for some very big advances. If 20 of us were to try to solve energy problems—with carbon capture and storage, or perhaps some other crazy idea—maybe one or two of us would

actually succeed. If nobody tries, we'll all certainly fail.

I believe the world will need to rely on nuclear energy. A looming energy crisis will force us to rework the underpinnings of our energy economy. That happened last in the 19th century, when we moved at an unprecedented scale toward gas and oil. The 20th century didn't require a big switcheroo, but looking into the 21st century, it's clear that we have a much bigger challenge.

As China, India, Brazil, and other parts of the developing world raise their standard of living, they'll want a lifestyle—and therefore a degree of energy consumption—that matches ours in the United States. Meanwhile, our own energy consumption increases. To meet these demands, the world's energy generation capability will have to multiply by a factor of at least five in this century, and possibly more.

What about renewable energy? Unfortunately, no such technology can completely replace fossil fuels, which provide base-load power whether or not the wind is blowing or the sun is shining. There is no carbon-free base-load power source except nuclear energy.

Let's be clear: conventional nuclear energy has drawbacks, principally that it relies on enriched uranium. That's problematic for several reasons. In the first place, there's not that much uranium: if you tried to scale conventional nuclear energy to meet the world's energy needs, you'd run out. And the enrichment process required to use natural uranium in today's light-water reactors is complicated, expensive, and wasteful. In the U.S., more than 700,000 metric tons of depleted uranium—the by-product of enrichment—sits in storage.

In the next few decades, we need more technology leaders to reach for some very big advances.

TerraPower's technology is designed to use that depleted uranium as fuel, turning the cheap by-product of today's reactors into enough electricity to power every home in America for 1,000 years. The technology would also nearly eliminate the need for new enrichment facilities, which is important because plutonium and enriched uranium, by-products of today's nuclear fuel cycle, can be used to make bombs.

TerraPower offers a path to zero-carbon, proliferation-resistant energy. Yes, there are a lot of challenges—scientific, engineering, and above all, political. The time it takes to develop a nuclear reactor and get it licensed is so daunting that it would be a crazy proposition for any ordinary entrepreneur.

But we are not going it alone or starting from a blank slate. TerraPower is building on decades of research at the U.S. national labs, and some of those labs are now doing contract work to help us perfect the designs. We're also working with the U.S. Nuclear Regulatory Commission and agencies in other countries to help governments understand the details of new types of reactors so that they can regulate them when the technology is ready for commercial deployment.

Though we believe there's a lot of good TerraPower can do for the world, it's a for-profit venture. It has to be: competing commercially is the only way any energy option can become sustainable. That said, TerraPower's investors, which include Khosla Ventures and Charles River Ventures, share the long-term view of its founders. They recognize that the biggest returns come from the biggest advances, and those take time.

Like Jeff Bezos and Elon Musk, I was once a little boy who played with model rockets and aspired to learn nuclear physics. Back then, the idea of science as a dynamic thing that can change lives was captivating.

It still is. Our challenge now, especially for those of us whose financial success is the greatest, is to think big.

Nathan Myhrvold is a founder and vice chairman of TerraPower, a founder and CEO of Intellectual Ventures, and former chief technology officer of Microsoft.

EMERGED TECHNOLOGIES

Should the Government Support Applied Research?

The ARPA-E research agency funds R&D that's not advanced enough for the private sector to take on. Now its focus on alternative energy puts it in the political crosshairs.

● Republican criticism of federal government efforts to fund new energy technologies has spilled over to ARPA-E, the U.S. Department of Energy's popular program for backing high-risk innovations in energy. Paul Ryan, now the Republican nominee for vice president, voted last year to slash the agency's budget, and presidential candidate Mitt Romney's energy plan says ARPA-E should focus on basic research.

Such views could rule out giving money to companies like Envia Systems, a 35-person startup located in Newark, California. Following a $4 million grant from ARPA-E, it says it's within sight of commercializing a high-capacity technology that could cut prices for electric-car batteries in half. "Venture capital funding took us half the way there, and the ARPA-E funding took us all the way there," CEO Atul Kapadia says.

The presidential campaign has revived the long-running policy debate over what role government should play in funding the development of new technologies. While almost everyone believes that it has a role in supporting basic research, the consensus breaks down at later and more expensive stages of development, such as demonstration projects. Historically, some Republicans have picked fights to keep agencies from giving grants for early-stage product research, a line that ARPA-E crossed intentionally when it was created in 2007. ⟶

Republican VP candidate Paul Ryan voted to cut funding for ARPA-E and says the government shouldn't "play venture capitalist."

AP/STEVEN SENNE

ARPA-E has funded around 200 projects, all of them meant to be "transformative" ways to either help replace foreign oil or reduce emissions. The notion is that such projects are too speculative and risky to gain large investments from companies. "I think it's hard to argue the types of investments that ARPA-E is making would be made by the private sector if ARPA-E did not exist," says Greg Nemet, an assistant professor of public affairs and environmental studies at the University of Wisconsin.

Envia Systems may never get its novel battery technology into vehicles. But it stands a better chance because of ARPA-E.

The agency, which had a modest budget of $180 million in 2011, has many fans in Congress, including among Republicans. That means it could avoid cuts and may see its budget increase. However, last year some House members said the agency should be defunded because its projects are too commercial and sometimes replicate work already paid for by the private sector. Critics claim one problem is that ARPA-E isn't able to find enough research that is truly transformative.

ARPA-E grants are meant to help move research ideas to the prototype or demonstration stage. Projects are given specific performance goals—such as increasing how much energy can be stored in a battery—that, if achieved, would take technology a few steps beyond the best commercial products. It has financed projects such as making liquid "electrofuels" directly from microörganisms fed electricity, chemicals, and carbon dioxide, as well as a flying wind turbine and new materials to capture carbon from coal plants.

At the agency, a team of scientists actively manage research programs. It's not uncommon for them to pull the plug if technical milestones aren't met. Such failures are partly by design. Grants are kept small (on average, about $3 or $4 million each)—part of an approach designed to pull a few winners out of a large pool of attempts.

While ARPA-E has generated exciting projects, it does have one clear flaw: a lack of end customers. "The big problem that makes energy different from most other startup enterprises is that even if you have something that works great, you probably never amass enough money to commercialize it," says Donald Paul, executive director of the University of Southern California's Energy Institute and former chief technology officer at Chevron.

That's where the Obama administration ran into trouble. The DOE tried to help some technologies toward large-scale commercialization, but after the bankruptcy of solar-panel maker Solyndra (recipient of a $535 million DOE loan guarantee), Republicans jumped in, accusing Obama of playing politics with technology. It became a campaign talking point: Ryan's website called for "getting Washington out of the business of picking winners and losers in the economy," including the energy sector. Although Romney has praised ARPA-E, he echoed the Republican concerns by saying that the agency should step back and concentrate on "basic research."

Such a shift would be at odds with ARPA-E's current grant portfolio. More than a third of the agency's grants have gone to companies (the rest go to universities and government labs), and nearly all of them are for applied research projects.

In the case of Envia, the company used its ARPA-E grant to finish development of an anode design for its prototype commercial battery pack. That wasn't basic research: there was a commercial goal. "It shortened our development time by two years," says Kapadia.

Envia Systems may never get its novel battery technology into vehicles. But it stands a better chance because of its ARPA-E funding. After seeing Envia's prototype batteries, General Motors invested $7 million in the startup. During a meeting with employees earlier this year, the automaker's CEO, Dan Akerson, said the battery technology could be a "game changer" for GM, judging that it stood a "better than 50-50 chance" of leading to an electric car that can go 200 miles on a charge.

He then gave what might be the perfect endorsement of ARPA-E. "These little companies come out of nowhere," said Akerson. "And they surprise you."

—Martin LaMonica

Spain's Lead in Renewable Energy

Renewable energy has grown far beyond what experts were predicting only a decade ago. Global wind and solar power production increased by more than 70 gigawatts in 2011 alone, and the two now yield a total of more than 600 gigawatts.

Spanish companies have taken advantage of their government's policies supporting renewables to build extensive wind farms, fields of solar photovoltaic (PV) panels, and serpentine twists of mirrors that make up solar thermal plants. Because they developed local expertise early on, Spanish companies quickly became international experts in a number of areas: wind and solar farm operations, turbine manufacturing, solar panel production, and solar thermal engineering.

Today, these companies are expanding into new markets in China, India, the Middle East, South America, and Africa, even as they continue to provide energy solutions in Europe and North America. As prices drop, inching ever closer to the cost of conventional energy, Spain's renewables experts are poised to take advantage of the robust market.

DIRECTING THE HEAT OF THE SUN

As the sun crosses a clear sky, a field of mirrors tilts up to catch its rays. Each mirror moves with the softest of clicks to meet the light, precisely angling those rays to the top of a tower, all the mirrors together concentrating the light and its heat on one blindingly bright spot. This tower system, one type of solar thermal power plant, is the latest solar technology to emerge from Spain.

Spanish companies are numbered among the world's leaders in the field of solar thermal, which is also known as concentrating solar power (CSP). This technology works by concentrating the sun's heat, then employing it to turn water into steam and turn a steam turbine. And—of particular interest to energy utilities—this energy can be stored as heat and used to generate electricity even after the sun has dipped below the horizon.

Most commercial projects to date have featured parabolic troughs, long lines of curved mirrors that snake along for miles and concentrate the sun's light along focal tubes. In addition to building such systems in Spain, Spanish companies are enjoying strong success in many other countries: Seville-based Abengoa is

in the process of building a 280-megawatt plant in Arizona that will incorporate storage in the form of molten salts, and has contracts for two more plants in California, while Pamplona-based Acciona built a solar thermal plant in Nevada that began operations in 2007, and, together with Barcelona-based Sener, was recently awarded a contract for a new plant in South Africa. Sener holds additional contracts for systems totaling 200 megawatts in India and for projects in the United States and Morocco.

Spain leads in solar thermal in part because its government retained a research facility in the hot, sunny south, long after the world's first rush of interest in the technology, sparked by the energy crisis of the 1970s, had waned. That center, along with other research and pilot sites that companies have built, provides the necessary facilities to investigate advanced technologies. Many solar thermal experts believe that while trough systems are a proven technology, the CSP systems of the future will eventually focus on the newer tower technology.

In a tower system, a field of heliostats (blocks of mirrors that change angles over the course of the day to catch the light) shine all the sunlight they reflect at the top of a tower. Since the sunlight is concentrated at one spot instead of along miles of tubes, the system can reach much higher temperatures than troughs do and is more efficient. The tower system's mirrors are flat instead of curved, and so are simpler to manufacture. Company representatives say this also means that tower systems built to the same scale as existing trough ones will be less expensive.

Only two companies in the world have so far built commercial-scale tower systems, both of them in southern Spain: Abengoa and Sener. (Other companies are now in the process of developing similar systems.) Abengoa built the first two commercial systems, PS10 and PS20. And in 2012, Sener's Gemasolar began operations. Sener's 19.9-megawatt tower system is the first commercial-scale tower system to incorporate storage in the form of molten salts (a combination of potassium nitrate and sodium nitrate). The salts absorb excess heat during the day and release it slowly into the evening hours.

While Sener had already employed molten salts in some of its trough systems, a tower receiver presented additional challenges. The salts had to be pumped up to the top of the tower, which had never been accomplished before. So Sener helped a pump manufacturer design a new pump that can withstand corrosive salts and high temperatures.

The focal point of a tower system is subjected to a bruising range of temperatures that can span hundreds of degrees in a single day. Jorge Sendagorta, Sener's president, explains that the company's experience in aerospace engineering proved critical, as satellites in space can also be exposed to temperature ranges of hundreds of degrees.

Based on the success of Gemasolar, Sener is now scaling up and designing systems that are two and three times that system's size, at a cost of about 40 percent less.

Abengoa's experience enabled the company to win the bidding for two plants in South Africa, one trough and one tower. For the 50-megawatt tower, it is employing a new technology called overheated steam, where water is subjected to temperatures of nearly 500 °C, 100 degrees hotter with the current technology. José Domínguez Abascal, chief technology officer of Abengoa, says the South African tower plant will be 25 percent more efficient than the company's towers in Spain. The overheated steam will also serve as a storage medium, because, like molten salts, it retains heat into the evening hours.

Domínguez-Abascal says that Abengoa is now investigating the use of heated gas, where compressed air is sent to the top of the tower and heated in place of steam. That high-pressure, high-temperature gas would operate a turbine. Such a system could be combined with a natural gas plant, also run by gas (as opposed to steam) turbines. Natural gas could be employed when solar power does not suffice; the two together would consume perhaps 30 percent of the natural gas required by a conventional natural gas plant, at a comparable operating cost. Abengoa recently unveiled a pilot plant in Seville that operates with heated compressed gas, and the company expects to offer a commercial-scale plant in only a few years.

PHOTO: GEMASOLAR

PV PANEL USE GROWS BRIGHTER

The use of solar photovoltaic (PV) panels has soared in recent years: installed PV worldwide has increased 75 percent, from 40 gigawatts in 2010 to nearly 70 gigawatts in 2011.

Many major Spanish renewable energy companies are involved in developing fields of photovoltaic panels. Abengoa recently signed a contract to build a 200-megawatt field in southern California; Acciona has a contract to build a PV field in South Africa; and Valencia-based Siliken will build a 100-megawatt power plant in Durango, Mexico. Isofotón, with headquarters in Malaga, has contracts for more than 300 megawatts of PV fields in the U.S. over the next three years, and, as a result, the company recently began manufacturing panels in Ohio.

Though the precipitous fall in the price of PV panels caused some international companies to close, this drop bodes well overall, says Carlos Navarro, president of the PV module manufacturer Siliken, because it opens up entirely new markets. While PV installations continue to grow in Europe and North Africa, emerging economies in South America, Africa, and Asia can now look to PV panels to supply power to urban centers, rather than relying on them primarily as an electricity source for rural villages for which connection to a power grid was prohibitively expensive.

The cost of solar power has dropped so significantly that, for some countries, "PV is cheaper than generating by other fossil fuels," Ángel Luis Serrano, CEO of Isofotón, explains. Spanish companies foresee coming opportunities in Brazil, Chile, India, and the Middle East.

China will also be a major market, adds Serrano. China installed three gigawatts of PV in 2011 and is expected to double that figure in 2012. Isofotón has established a joint venture with a Chinese company and is already entering into agreements with utility companies for ground-based solar systems.

While the largest new projects today provide energy to urban centers, Isofotón and Atersa began working in rural electrification projects when both companies were founded more than 30 years ago. Virgilio Navarro, CEO of Valencia-based Atersa, says that although rural electrification is only 10 percent of Atersa's business today—Atersa has projects in Europe and North America as well as South America and the Middle East—its expertise, built up over decades, provides invaluable knowledge when, for instance, supplying power for a solar-powered water pump in Africa.

Spanish solar companies are investing in the development of increasingly efficient solar cells. Isofotón's efforts have led to cells with 18.7 percent efficiency, and the company hopes to reach 20 to 21 percent. The increase in efficiency can lead to significant reduction in materials and overall cost. Isofotón's researchers have also focused on high-concentration PV, or HCPV, a technology that tracks the movement of the sun and operates optimally in direct sunlight at high temperatures, in locations such as northern Chile and California's Mojave Desert—even in some regions of Spain and Italy. Last year, Isofotón decided to move its technology out of the laboratory into mass production. The company now has small HCPV installations in Spain, China, and Morocco, and will soon install systems in Abu Dhabi and build a larger HCPV field in northern Chile.

Siliken recently opened a new pilot manufacturing center near the company's Valencia headquarters. This facility acts as a manufacturing R&D center, where researchers can evaluate the manufacturing processes for new technologies before scaling up.

Siliken's first small-scale production line involves a limited production of new back-contact solar cells. Only one other company in the world has developed such cells, which obviate the need for metal grids—traditionally placed on the front of solar panels—that interfere with their efficiency. In the lab, these new panels reach an efficiency of 24.2 percent. Siliken's engineers are also evaluating techniques to reduce the thickness of wafers, to reduce the use of silver (which contributes a significant percentage of the overall cost of a solar cell), and to eliminate lead from the manufacturing process.

Isofotón's Serrano predicts that the future of solar power will see installations on rooftops and integrated into buildings. In Japan, for instance, the recent Fukoshima tragedy has led to a reconsideration of nuclear power; all 54 nuclear plants were taken off line for evaluation, and only a few have been brought back on line. Local and national Japanese governments are encouraging renewable energy, and the PV market in Japan has skyrocketed.

Onyx Solar, based outside Madrid, has developed integrated PV solutions for construction materials, such as canopies, floors, and nearly transparent PV skylights. These materials, which also provide thermal insulation and protection from damaging UV rays, are custom developed for each project according to the customer's needs.

Just such an energy-generating skylight slants over the bustling new San Antón market in Madrid's Chueca neighborhood. In addition to installations in Spain, Onyx has completed projects in China, Italy, France, and the U.S., and currently has more than 300 projects in the design phase. Most recently, Onyx was selected by Turner Construction to develop the largest PV skylight in the U.S., which will be integrated into the new Novartis headquarters in New Jersey.

PHOTO: GAMESA

WIND BLOWS STRONG

A massive wind power turbine floats offshore, tethered to the ocean floor far beneath it. The balancing weight beneath the turbine allows it to stay upright despite the swells of the waves.

Such a deep-water offshore turbine is the focus of the Acciona-led European project called HiPRWind (pronounced "hyperwind"). Acciona tested a version of a floating turbine in a defense facility near Madrid in the spring of 2012, and is designing two pilot turbines that will float off Spain's coast, the first by the fall of 2013.

Most offshore wind power installations in development have been constructed or are planned for the relatively shallow waters of Northern Europe, and these operate by way of turbines that sit atop fixtures attached solidly to the sea's floor. But as turbines become larger, and offshore wind moves into deeper waters, floating turbines (none of which are commercially available thus far), will be the necessary solution, says Raul Manzanas, Acciona's research director for on- and offshore wind, because fixed turbines in deep water are prohibitively expensive. Acciona, which both manufactures turbines and operates wind farms, is now developing 6-megawatt floating turbines.

And while the floating solutions are under development, offshore wind development is already booming in Northern Europe, and all the Spanish wind power companies—international leaders in turbine manufacturing and wind farm operations—are moving into offshore wind.

Álvaro Martínez, Iberdrola's offshore manager, spreads out a huge map of northern Europe, delineating wind farms either under construction or contracted in the Irish, North, and Baltic Seas. These farms range from a 400-megawatt farm—larger than nearly all onshore farms—to ones that will supply seven to ten thousand megawatts to nearby countries.

Even 100 miles from shore, the waters remain shallow enough for a fixed platform. The region has strong winds and is close to many major European population centers. Iberdrola is involved in two offshore wind farms there, one 400-megawatt farm in the Irish Sea, already in construction, and another 7.2-gigawatt one in the North Sea, which will be the second largest in the world, behind only another planned North Sea wind farm. The power will be generated close enough to London that Madrid-based Iberdrola has already secured a market for the wind farm's entire future power output. Construction will begin in 2015 and continue throughout the second part of the decade.

And though fixed offshore wind turbines are commercially available, this rapidly growing market still presents challenges in transportation, construction, energy delivery, and maintenance. Iberdrola is working on a number of research projects to develop solutions to these challenges.

Onshore wind power, a relatively mature technology, remains strong: despite economic challenges, wind power grew by 21 percent from 2010 to 2011. In addition to continued expansion in Europe and North America, significant growth is taking place in China and India, and in new markets in Latin America, Asia, and Africa.

Spain's government enacted measures that strongly supported the expansion of wind power in Spain, and as a result, many of the top international wind power companies are Spanish. Iberdrola is the world's largest wind power operator, running more than 14 gigawatts of wind farms across more than 20 countries.

Acciona builds turbines and operates wind farms on four continents. The company recently opened three wind parks in the Mexican state of Oaxaca, making it the leading wind power operator in Mexico, and it is supplying wind turbines and initial operations for a new wind farm in Montana. (Acciona already operates a turbine factory in Iowa). Gamesa, a leading turbine manufacturer, has factories in Europe, the U.S., Asia, and Brazil, and turbines installed in 35 countries. Gamesa recently supplied 152 turbines for the new 304-megawatt Blue Creek wind farm in Ohio, which Iberdrola is constructing and will operate. This will be the largest wind farm in the U.S., and one of the largest in the world.

Experts say the potential for onshore wind power is nowhere near tapped out, with existing markets continually expanding and new ones emerging. The technology has decades of demonstrated success, and innovations continue in fields such as wind forecasting and in new materials and manufacturing techniques for larger turbines. For instance, Gamesa's new 4.5-megawatt turbine's modular blade, the longest of the onshore blades, is made of a lightweight composite material that can be easily transported and assembled. Gamesa is also innovating in offshore wind power, and is developing a 5-megawatt turbine for offshore wind that may supply future ocean-based wind farms.

In wind power and solar power alike, Spanish companies remain leaders in the field, and continue to develop creative technologies and innovations to lead the market in the future.

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Reviews

Old Media, Digitized, Make New Forms

Computers are changing art in unexpected ways.

By Martin Gayford

Untitled
Urs Fischer, 2011
Wax, pigments, wicks, steel
On view at the 2011 Venice Biennale (pictured right)

Exposure
Antony Gormley, 2010
Steel girders
Lelystad, the Netherlands

The Vanity of Small Differences
Grayson Perry, 2012
Tapestry
On view at the Victoria Miro Gallery, 2012

Penelope's Labour: Weaving Words and Images
Fondazione Giorgio Cini, Venice, 2011

On July 6, 1507, Michelangelo wrote from Bologna to his brother, Buonarroto. He was engaged in casting a colossal bronze sculpture, of Pope Julius II, and because he was not an expert in bronze casting, he had sent to Florence for someone who was: Bernardino d'Antonio del Ponte di Milano, Master of Ordnance to the Republic of Florence. Michelangelo had great faith in him, he told his brother: "I could have believed that Maestro Bernardino could cast without fire." Though the initial attempt had not gone well, he hoped that with "a great deal of anxiety, exertion, and expense" they would eventually succeed—as indeed they did, although later the statue was melted down by the pope's enemies and transformed, ironically, into a cannon.

Fast-forward a little over half a millennium, and the contemporary Swiss artist Urs Fischer was also facing a technical challenge. He wanted to make a perfect facsimile of Giambologna's intertwined three-figure marble sculpture *The Rape of the Sabine Women* (1582) in candle wax (plus wax sculptures of an office chair and an artist friend of his named Rudolf Stingel). Just like Michelangelo, he sought out technical assistance—in his case Kunstgiesserei, an art foundry at St. Gallen in Switzerland. The original 16th-century sculpture, in the Loggia dei Lanzi in Florence, was digitized by a state-of-the-art optical scanner, and the resulting information was used to create a model, then a mold, and, eventually, a sculpture in wax, precisely mimicking the stone of the original—plus wicks.

The wax statue slowly burned throughout the 2011 Venice Biennale, in the center of a display of contemporary art in the Arsenale. At the beginning only the figures' fingertips and other extremities were alight; at the end nothing was left except a few distorted remnants. This was an aesthetic meltdown, an image of time and its deconstruction of form. It was one of the spectacular sights of the Biennale.

In one respect, there was little difference between the ways these works were made. Each artist had an idea and needed technical assistance to realize it. Michelangelo required Bernardino to help him cast a big bronze sculpture, a technical challenge for Renaissance artists (contemporary eyewitness accounts describe him taunting Leonardo da Vinci for his inability to cast a gigantic horse in Milan). Fischer wanted to make a perfect copy of *The Rape of the Sabine Women* in wax, and digital scanning gave him the help he needed.

The point, as Fischer emphasized in an interview with *The Art Newspaper* this spring, is that digitization is everywhere in the contemporary world—including the artist's studio. "People see I use computers, so they say I'm making computer art," he said. "It's not about making computer art; it's just using the new thing. Everybody uses it." To carry out certain ideas, new technology is essential—or to put it another way, computer technology is making possible projects that only a few years ago would have been utterly unfeasible.

Artists are using computer systems in all manner of time-honored art forms. Painters such as Jeff Koons and Michael Craig-Martin construct images using a method of computer screen "collaging" (that is, by selecting and assembling images from various sources digitally), and when they have the visual result they want, they make it into a painting (or, in Koons's case, hand it over to assistants to reproduce in paint). In other cases, new technology makes a wild idea practicable. It is now common for artists to digitally scan an image, manipulate its perspective and colors, and then project the result onto a canvas upon which they paint.

Monumental sculpture, meanwhile, has always been at least partly a matter of engineering, and the bigger the project, the trickier it is to realize. Take Antony Gormley's *Exposure*: a nearly 85-foot-high, 60-ton crouching figure made out of steel girders, unveiled on a spit of land near the shore of the Zuiderzee in 2010. The essential idea—a gigantic sculpture of a male figure—is a simple one. As a matter of fact, it is one that Michelangelo had but was unable to execute. Condivi's *Life of Michelangelo* records that while he was quarrying at Carrara, one day the idea came into his mind of carving an entire mountain into a figure. Later, he remarked, "If I could have been sure of living four times longer than I have lived I would have taken it on." The mechanical stonecutting equipment necessary for Michelangelo's project didn't actually come along until the 19th and 20th centuries. The art that gets made is naturally limited by the technology available—but that doesn't stop artists from having notions that exceed those limits.

Gormley's idea for *Exposure* was more modest than Michelangelo's, but it was nonetheless on the edge of technical feasibility. He wanted to make a human figure that would respond to changes in sea level caused by global warming: sited on a sea dike, it may disappear if the Zuiderzee rises. "Over time," Gormley writes on his website, "should the rising of the sea level mean that there has to be a rising of the dike, this means that there should be a progressive burying of the work."

Exposure
Antony Gormley,
2010
Steel girders

Digitization was vital to realizing the idea. *Exposure* required it at almost every stage. The starting point was a plaster cast of Gormley himself, but the artist wanted to translate this into an openwork structure of steel girders in the most economical fashion: that is, to find the pattern of metal struts that described the body in the smallest number of components.

Obviously, *Exposure* was a novel engineering project as well as an artistic one. It was a sculpture made using techniques employed for bridges. But a human figure is quite unlike a bridge, its geometry complex and curvaceous. Solving the problems involved in making *Exposure* required several separate teams of specialists. First, software developed by Roberto Cipolla and his team at the University of Cambridge transformed photographs of the cast into a fully rotational 3-D computer model. This was then translated into an open steel lattice with help from an algorithm devised by Sean Hanna of University College London. Next, engineers at Royal Haskoning drew up a detailed design. Using a webcam, the engineers then monitored the construction process—carried out by the Scottish steel fabrication firm Had-Fab—to ensure that the sculpture was developing as it should. *Exposure* could not have been created 10 years ago.

New technology had also helped Gormley bring a number of earlier projects to fruition. Much of his work has had to do with finding novel physical equivalents to the human form—often, his own naked physique. The series *Insiders* (1997–2003) was made by reducing the volume of the human body by 70 percent, while retaining dimensions such as height. The result was spiky, spectral figures of a kind never quite seen before. Although the first series was worked out

Pixelation of a Hybrid
Marc Quinn
2011
Tapestry

using mechanical templates, the second—entitled *Inside Australia*—was produced by scanning naked inhabitants of Menzies, an Outback community. The scans went through a process the technicians nicknamed "Gormleyization." Horizontal sections were taken of each; they were reduced by two-thirds and the contours joined. The digital files were sent to a polystyrene mill in Sydney, where they were turned into patterns. These were sent to a foundry in Perth in a form that the architect Finn Pedersen, who was assisting Gormley, described as "a giant model aeroplane kit," and finally they were cast in an alloy of iron, molybdenum, iridium, vanadium, and titanium.

Technology was yet more crucial to Gormley's *Quantum Cloud* (1999), commissioned for a site on the Thames in London. A computer-aided design program configured a mass of galvanized steel units into a nearly 30-meter-high cloud, in whose center the fuzzy form of the artist's body seems to condense.

These are all cases of new technology applied to a very old art form: figurative sculpture. Concurrently, the almost equally antique medium of tapestry was undergoing a digital transformation. When Michelangelo's contemporary Raphael designed a set of tapestries for the Sistine Chapel in 1515–16, the process involved first making full-scale painted versions. These were completed by the artist and his workshop in Rome before being sent to the workshop of Pieter van Aelst in Brussels. There, Raphael's designs were woven into textiles of wool, silk, and gilt-wrapped thread. The process involved placing the paintings underneath the looms. Raphael's original works—the so-called cartoons, on display at the Victoria and Albert Museum in London—are now regarded as among the greatest masterworks, but essentially they were files that were used to weave multiple sets of tapestries for centuries before they were resurrected as independent works of art.

In some ways, not much has changed. High-quality tapestry is still often manufactured in Belgium. An example is *The Vanity of Small Differences*, a series of tapestries by the British artist Grayson Perry that was on exhibit at the Victoria Miro Gallery during the summer of 2012. These were designed in collaboration with Factum Arte, a Madrid-based organization dedicated to creating art through digital means, and woven from digital files in Flanders. Though Perry's quirky graphic style is different—rooted in the work of untrained painters, known as "outsider art"—the process of creating the tapestries was a digital version of the procedure Raphael followed.

But developments in tapestry technology are also opening some new possibilities. Weaving and computing are, as it happens, interconnected historically, as was emphasized by "Penelope's Labour," an exhibit (curated by Factum Arte) at the 2011 Venice Biennale.

The mechanized Jacquard loom, invented by Joseph Marie Jacquard in 1801, operates by the use of punched cards—which in turn gave Charles Babbage the inspiration for his unrealized "analytic

engine." An article on the engine, written in French by the Italian mathematician Luigi Menabrea, was translated by the poet Byron's daughter Ada, Countess Lovelace. In her annotations to Menabrea's article, Lovelace wrote what is believed to be the first computer program.

In the last few years, mechanical weaving, driven by digitized designs, has reached a point where it is possible to reproduce a photographic image in threads, with fine detail and smooth tonal transitions. In the past, that was always the technical hurdle for tapestry: the reason Raphael cartoons had to be transported halfway across Europe to Van Aelst's workshop was that there the craftsmen were enormously skillful at re-creating the effects of painting in threads.

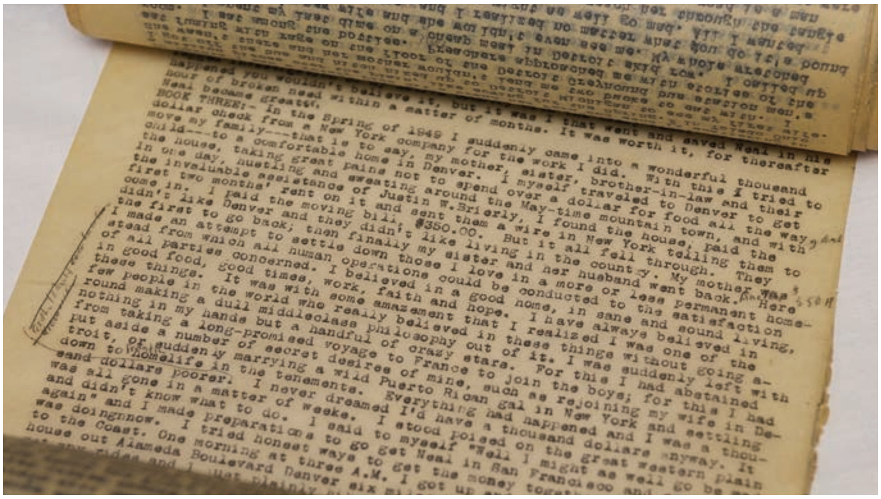
The possibility of transforming a photograph into a tapestry was exploited by some artists in the "Penelope's Labour" exhibition, including the Cuban Carlos Garaicoa and Britons Marc Quinn and Craigie Horsfield. Garaicoa showed textiles woven from shots of the Havana pavement, Quinn gigantic blowups of flowers—neither part of the medium's traditional repertoire.

Horsfield explained his interest in this venerable art form to *Modern Painters* magazine: "Tapestry was going through a technical change, a really radical technical change, which allowed you to do things that you previously hadn't been able to do." It had been impossible to reproduce a photograph without the tonal gradient breaking up into banding. Then, suddenly, in the early 21st century it could be done. In "Slow Time and the Present," an exhibition at the Kunsthalle Basel in Switzerland last summer, Horsfield showed wall-sized tapestries based on street scenes in southern Italy, a circus in Barcelona, and a zoo in Oxford. (He also displayed yet another novelty: digitally printed frescoes.)

The visual effect was old and simultaneously new. Horsfield's crowd scenes bring the shadowy drama of Caravaggio's paintings irresistibly to mind. On the other hand, a camera image metamorphosed into a monumental fabric is something novel: it's a photograph given the luxurious surface and scale of the grandest art of the past.

Art is like that: a lot of the aims haven't altered since the days of Lascaux. But new technical means are constantly evolving, and that—as Michelangelo would have ruefully appreciated—profoundly affects what artists can actually make.

Martin Gayford is the chief art critic for Bloomberg News.


hour of broken need within a matter of months. It was worth it, for thereafter
Neal became greater.
BOOK THREE:- In the Spring of 1949 I suddenly came into a wonderful thousand
dollar check from a New York company for the work I did. With this I tried to
move my family---that is to say, my mother, sister, brother-in-law and their
child---to a comfortable home in Denver. I myself traveled to Denver to get
the house, taking great pains not to spend over a dollar for food all the way,
In one day, hustling and sweating around the May-time mountain town, and with
the invaluable assistance of Justin W.Brierly, I found the house, paid the
first two months' rent on it and sent them a wire in New York telling them to
come in. I paid the moving bill, $350.00. But it all fell through. They
didn't like Denver and they didn't like living in the country. My mother was
the first to go back; then finally my sister and her husband went back. Here
I made an attempt to settle down those I love in a more or less permanent home-
stead from which all human operations could be conducted to the satisfaction
of all parties concerned. I believed in a good home, in sane and sound living,
in good food, good times, work, faith and hope. I have always believed in
these things. It was with some amazement that I realized I was one of the
few people in the world who really believed in these things without going a-
round making a dull middleclass philosophy out of it. I was suddenly left with
nothing in my hands but a handful of crazy stars. For this I had abstained
from taking a long-promised voyage to France to join the boys; for this I had
put aside a number of secret desires of mine, such as rejoining my wife in De-
troit, or suddenly marrying a wild Puerto Rican gal in New York and settling
down to homelife in the tenements. Everything had happened and I was a thou-
sand dollars poorer. I never dreamed I'd have a thousand dollars anyway. It

The stream-of-consciousness lyricism of On the Road *derives in no small part from the fact that Kerouac typed it on a continuous scroll of paper.*

How Authors Write

The technologies of composition, not new media, inspire innovations in literary styles and forms.

By Jason Pontin

Early in Nicholson Baker's slim first novel, *The Mezzanine* (1988), whose entire action takes place during an escalator ride at lunchtime, the narrator describes buying milk and a cookie, and then pauses to consider, in a page-long footnote, the "uncomfortable era of the floating drinking straw":

> I stared in disbelief the first time a straw rose up from my can of soda and hung out over the table, barely arrested by burrs in the underside of the metal opening. I was holding a slice of pizza in one hand, folded in a three-finger grip so that it wouldn't flop and pour cheese-grease on the paper plate, and a paperback in a similar grip in the other hand—what was I supposed to do? The whole point of straws, I had thought, was that you did not have to set down the slice of pizza to suck a dose of Coke while reading a paperback.

Baker speculates about how the straw engineers had made "so elementary a mistake," designing "a straw that weighed less than the sugar-water in which it was intended to stand"; pardons the engineers who had forgotten to take into account how bubbles of carbonation might affect a straw's buoyancy; explains how such unsatisfactory straws came to be sold to restaurants and stores in the first place; and, in a kind of musical resolution, concludes by remembering the day when he noticed a plastic straw, "made of some subtler polymer," once again anchored to the bottom of a soda can.

The point of this footnote and 49 like it is to subject everyday objects to such close attention that they will, in the words of Sam Anderson in the *Paris Review*, "start to glow with significance." Justifying the footnotes (in another footnote), Baker writes that "the outer surface of truth is not smooth, welling and gathering from paragraph to shapely paragraph, but is encrusted with a rough protective bark of citations, quotation marks, italics, and foreign languages, a whole variorum crust of 'ibid.'s' and 'compare's' and 'see's' that are the shield for the pure flow of argument as it lives for the moment in one mind."

Writers had used short footnotes for artistic effect before *The Mezzanine* (Borges, for one, had employed them as dusty jokes). But when Baker told Anderson that "nobody was doing footnotes back then," he was plausibly laying claim to an innovation: footnotes so long and involved they drowned the narrative, so that the reader, like a disoriented swimmer, would surface at the note's termination, spluttering, "Where am I?"

How did Baker invent such a literary device, which afterward grew to overluxuriant complexity in the writings of David Foster Wallace and his imitators (including the infamous "Host," which is mostly footnotes, and where Wallace attempted a footnote to a footnote to a footnote)?

As it happens, we know. Baker says he wrote *The Mezzanine* on an early portable computer called the Kaypro, "a really lovely machine" with "two floppy drives" that "looked like a small ... piece of medical equipment." He had always loved footnotes; the Kaypro's word processing program made it easy to insert and format them. A typewriter would have placed natural limits on the length of a footnote. Had the thought occurred, a very determined Baker might have added long footnotes by re-creating Proust's "paperoles," those additional sheets of paper that the French writer glued to the manuscript of *À la recherche du temps perdu* in order to elaborate endlessly upon his characters. But the Kaypro invited expansiveness,

DARRON CUMMINGS / ASSOCIATED PRESS

and Baker accepted. Wallace and others followed, performing similar tricks with the software they used.

At a time when new media are proliferating, it is tempting to imagine that authors, thinking about how their writing will appear on devices such as electronic readers, tablet computers, or smartphones, consciously or unconsciously adapt their prose to the exigencies of publishing platforms. But that's not what actually happens. One looks in vain for many examples of stories whose style or form has been cleverly adapted to their digital destinations. Stories on e-readers look pretty much as stories have always looked. Even The Atavist, a startup in Brooklyn founded to publish multimedia long-format journalism for tablet computers, does little more than add elements like interactive maps, videos, or photographs to conventional stories. But such elements are editors' accretions; The Atavist's authors have not been moved, as Baker was, by the creative possibilities of a new technology. Writers are excited to experimentation not by the media in which their works are published but, rather, by the technologies they use to compose the works.

There have been odd exceptions, of course. In *Tristram Shandy*, published from 1759 to 1767, Laurence Sterne employed all the techniques of contemporary printing to remind readers they held a book: there is a black page that mourns the death of a character, a squiggly line drawn by another character as he flourishes his walking stick, and on page 169, volume 3, of the first edition a leaf of paper marbling, a type of decoration that 18th-century bookbinders offered their wealthier clients. With this technology, pigments are suspended upon water or a viscous medium called "size," creating colorful swirls, and are then transferred to a paper laid by hand upon the liquid. Each copy of the first edition of *Tristram Shandy* thus included unique marbling; the process was so expensive and time-consuming that later editions printed a monochrome reproduction instead. Sterne, an eccentric and tubercular Anglican priest, badgered his publisher, Dodsley, to include the page (which he called "the motley emblem of my work") in order to suggest something about the opacity of literary meaning.

Yet such responses to publishing technologies are rare. Besides the way Baker and Wallace used the "Insert Footnote" function in word processing software, writers have more often found inspiration in typewriting, photocopying, blogging, and, most recently, presentation software such as Microsoft PowerPoint and social media like Twitter.

Jack Kerouac claimed to have written *On the Road* in 1951 during a three-week, Benzedrine-fueled delirium of "spontaneous prose," typing continuously onto a 120-foot roll of teletype paper. In reality,

The Mezzanine
Nicholson Baker
Weidenfeld and Nicholson, 1988

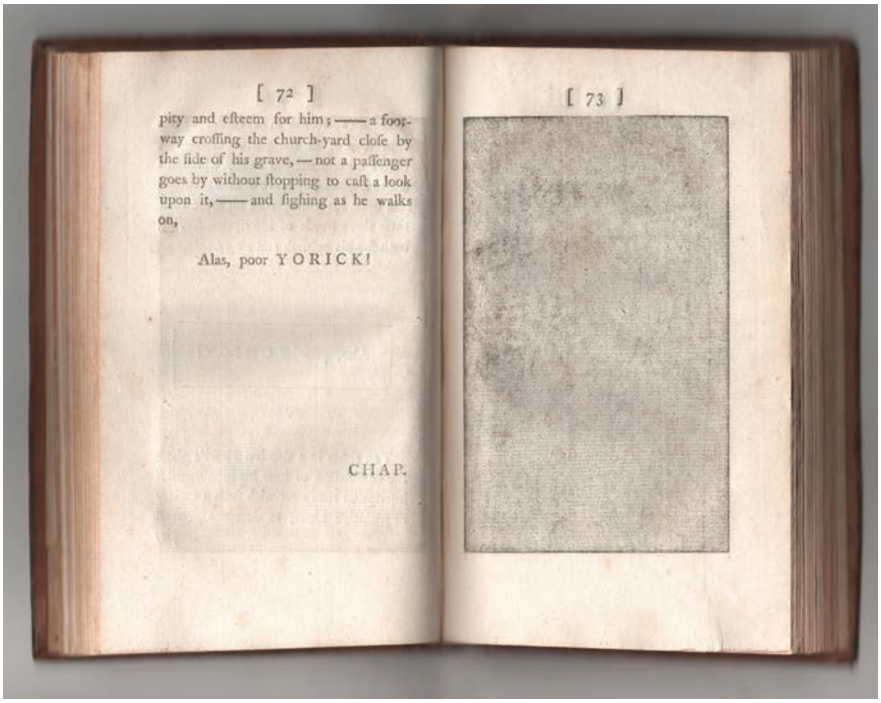
"Host"
David Foster Wallace
from *Consider the Lobster*
Little, Brown, 2005

The Life and Opinions of Tristram Shandy, Gentleman
Laurence Sterne
R. and J. Dodsley, 1759–1767

On the Road
Jack Kerouac
Viking, 1957

The Emigrants [Die Ausgewanderten]
W. G. Sebald
Vito von Eichborn, 1992

A Visit from the Goon Squad
Jennifer Egan
Alfred A. Knopf, 2010



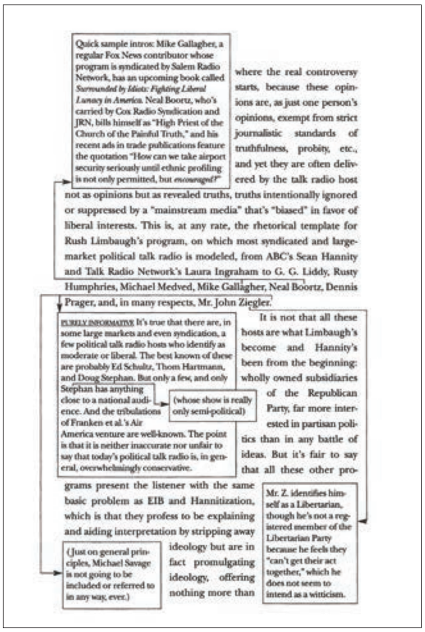
[72]

pity and eſteem for him; —— a foot-way croſſing the church-yard cloſe by the ſide of his grave, — not a paſſenger goes by without ſtopping to caſt a look upon it, —— and ſighing as he walks on,

Alas, poor YORICK!

CHAP.

[73]



Quick sample intros: Mike Gallagher, a regular Fox News contributor whose program is syndicated by Salem Radio Network, has an upcoming book called *Surrounded by Idiots: Fighting Liberal Lunacy in America*. Neal Boortz, who's carried by Cox Radio Syndication and JRN, bills himself as "High Priest of the Church of the Painful Truth," and his recent ads in trade publications feature the quotation "How can we take airport security seriously until ethnic profiling is not only permitted, but *encouraged?*"

where the real controversy starts, because these opinions are, as just one person's opinions, exempt from strict journalistic standards of truthfulness, probity, etc., and yet they are often delivered by the talk radio host not as opinions but as revealed truths, truths intentionally ignored or suppressed by a "mainstream media" that's "biased" in favor of liberal interests. This is, at any rate, the rhetorical template for Rush Limbaugh's program, on which most syndicated and large-market political talk radio is modeled, from ABC's Sean Hannity and Talk Radio Network's Laura Ingraham to G. G. Liddy, Rusty Humphries, Michael Medved, Mike Gallagher, Neal Boortz, Dennis Prager, and, in many respects, Mr. John Ziegler.

PURELY INFORMATIVE It's true that there are, in some large markets and even syndication, a few political talk radio hosts who identify as moderate or liberal. The best known of these are probably Ed Schultz, Thom Hartmann, and Doug Stephan. But only a few, and only Stephan has anything close to a national audience. And the tribulations of Franken et al.'s Air America venture are well-known. The point is that it is neither inaccurate nor unfair to say that today's political talk radio is, in general, overwhelmingly conservative.

(whose show is really only semi-political)

It is not that all these hosts are what Limbaugh's become and Hannity's been from the beginning: wholly owned subsidiaries of the Republican Party, far more interested in partisan politics than in any battle of ideas. But it's fair to say that all these other programs present the listener with the same basic problem as EIB and Hannitization, which is that they profess to be explaining and aiding interpretation by stripping away ideology but are in fact promulgating ideology, offering nothing more than

Mr. Z. identifies himself as a Libertarian, though he's not a registered member of the Libertarian Party because he feels they "can't get their act together," which he does not seem to intend as a witticism.

(Just on general principles, Michael Savage is not going to be included or referred to in any way, ever.)

The Emigrants

honeysuckle, shortly before we left for a holiday in France. A few weeks after, late that summer, he took his own life with a bullet from his heavy hunting rifle. He had sat on the edge of his bed (we learnt on our return from France) with the gun between his legs, placed the muzzle of the rifle at his jaw, and then, for the first time since he bought the gun before

2 3 JUIL 1986

Trois fois coup sur coup dans les Alpes

Des linceuls s'

Hier, on a identifié le cadavre d'un guide disparu en 1914

Mais le phénomène des glaces qui rendent leurs victimes e

L'histo

◇ 22 ◇

Clockwise from top: The famous black page in Tristram Shandy; *a typical page in W.G. Sebald's* The Emigrants, *combining type with a newspaper clipping; and a heavily footnoted page from David Foster Wallace's "Host."*

he worked from dozens of small notebooks kept during his years on the road with Neal Cassady, typed on a homely roll created by taping together sheets of tracing paper, and revised the scroll's text at leisure; but his first draft really was produced without paragraph breaks on a continuous roll of paper. (The scroll still exists—except for its final section, where Kerouac laconically scrawled, "Ate by Patchkee, a dog"—and is on display at the British Library in London until the end of the year.)

If the physical artifact of the scroll is astonishing to see, the prose it made is celebrated for its ecstatic lyricism. It was a tremendous influence on Allen Ginsberg and all the Beat writers who wanted a jazzy style commensurate with the manic energy of postwar America:

> So in America when the sun goes down and I sit on the old broken-down river pier watching the long, long skies over New Jersey and sense all that raw land that rolls in one unbelievable huge bulge over to the West Coast, and all that road going, and all the people dreaming in the immensity of it, and in Iowa I know by now the children must be crying in the land where they let the children cry, and tonight the stars'll be out, and don't you know that God is Pooh Bear?

Tools of typing are not the only technologies of composition that can inspire. The German writer W.G. Sebald composed strange meditations, neither obviously fiction nor nonfiction, about the terrible events of the 20th century. He once said of the Holocaust that "no serious person thinks of anything else," but he approached the subject obliquely. His books begin quietly ("At the end of September 1970, shortly after I took up my position at Norwich, I drove out to Hingham in search of somewhere to live," and "In the second half of the 1960s, I traveled repeatedly from England to Bel-

gium") but pursue a deteriorating orbit around the central tragedy, like a satellite falling into a sun. *The Emigrants* (in German, *Die Ausgewanderten*), published in 1992, seems a straightforward account of the blighted lives of four Germans in exile; only gradually does the reader sense all the missing, those who never escaped but died. In *Austerlitz* (2001), Sebald feels his way through the life of the eponymous hero, brought to England in 1939 aboard a *Kindertransport*, raised by adoptive Nonconformist parents in Wales, who, late in life, returns to Prague and Paris in order to learn the fate of his biological parents.

The books are notable for their formal qualities: virtuosic digressions, descents into the past through nested narrators, and convoluted sentences that extend over many pages. Most idiosyncratic of all is Sebald's use of uncaptioned, grainy black-and-white photographs. Some are clippings from newspapers and magazines; others are snapshots, taken with Sebald's little Canon camera; others are of buildings, presumably destroyed in the Allied bombing, and many more of people, also presumably lost. The photographs have the melancholy air of found art; but while the author implies that some of the photos were found in his family's photo albums, he does not say which. After Sebald died in a car crash in 2001, the *Guardian*'s obituary recalled how he constructed his books at the University of East Anglia, in England, where he was a professor of European literature: "He was an exacting customer at the University's … copy shop, discussing what might be done with his images, adjusting the size and contrast." Sebald is really inimitable; but that has not stopped hundreds, including Will Self, from trying, so that "Sebaldian" (which mostly means a mournful combination of long sentences and photographs) has become a critics' adjective.

Even when a writer's style is informed by a publishing platform, it's more often because that technology is also an authoring tool: blogging programs, such as Movable Type or WordPress, are content management systems that publish blogs to the Web, but they are also sophisticated word processors that make it easy to link to other blogs, use block quotes, or embed photographs and videos. The distinctive voice of modern bloggers—impulsively reactive, colloquial, intimate, allusive, and, above all, chatty—owes much to such software. Emily Gould, who has contributed to *MIT Technology Review*, is as responsible as anyone for the reigning style. In 2006, her blog, Emilymagazine, was noticed by the editors of Gawker, who hired her to write gossip about other young people working in media in New York. She was funny, acute, and oversharey; she became a microcelebrity and found her manner and coinages aped by other bloggers. Gould soon left Gawker tired of gossip, and became more circumspect, but she is still funny. A not untypical post on Emilymagazine, from 2010, begins:

> While researching a This Recording post about how Joni Mitchell and Graham Nash's love affair affected their respective artistic outputs—because, I guess, I have assigned myself to be the Us Weekly of 40 years ago?—I fell into a YouTube odyssey of Graham Nash's British Invasion band The Hollies, specifically, an odyssey of iterations of this song, Carrie-Anne.

The sentence is packed: preceded by an embedded video, it self-referentially links to another post, alludes to shared assumptions about celebrity magazines, parodies the modern-girlish habits of self-deflation and what linguists call "high rising terminals" (where pitch rises to a kind of pseudoquestion), and introduces the subject of the post, a saccharine example of '60s pop.

A recent example of how authoring tools can suggest novel styles of writing can be found in Jennifer Egan's *A Visit from the Goon Squad*, which won the 2011 Pulitzer Prize for fiction. The novel, a collection of 13 interconnected short stories, describes the depredations of time (the goon squad of the title, because "time's a goon") upon a cast of characters who first meet in San Francisco's punk scene in the late 1970s. Chapter 12, "Great Rock and Roll Pauses," is written in the form of a series of Microsoft PowerPoint slides (complete with bullet points, Venn diagrams, and other infographics) and presented as the creation of Alison, the 12-year-old daughter of one of the protagonists. Ally resorts to PowerPoint because it is her native idiom; but Egan obviously delighted in overcoming the artificial constraints of the format in order to tell the simple story of a girl's relationship with her autistic brother and his pathetic obsession with musical pauses. (The author has posted Ally's slides with their accompanying music on her website.)

Egan continues to be inspired by technologies of composition. Last spring, she published a short story on the *New Yorker*'s twitter account, @NYerFiction, entirely in the form of tweets. The story,

Writers are excited to experimentation not by the media in which their works are published but, rather, by the technologies they use to compose the works.

"Black Box," was later printed in an issue of the magazine devoted to science fiction. Egan has explained that she wanted to write a story that would seem to be told inadvertently, using a narrator's notes to herself: "My working title for this story was 'Lessons Learned,' and my hope was to tell a story whose shape would emerge from the lessons the narrator derived from each step in the action, rather than from descriptions of the action itself." In the story, a "beauty," a spy working in the south of France to seduce and collect intelligence from a repellent "Designated Mate" and his colleagues, records a mission log that she and her fellow beauties might later find helpful. Because the logs are silent self-communings, and because she is alone, the overwhelming impression is of the narrator's vulnerability and bravery:

> The first thirty seconds in a person's presence are the most important.
>
> If you're having trouble perceiving and projecting, focus on projecting.
>
> Necessary ingredients for a successful projection: giggles; bare legs; shyness.
>
> The goal is to be both irresistible and invisible.
>
> When you succeed, a certain sharpness will go out of his eyes.

Egan, Gould, Sebald, Kerouac, and Baker were all writing in eras when new media were everywhere, but what computer scientists call "platform shift" did not get their juices going. The technologies of composition did. Why this should be so is not mysterious. The explanation is that literary writers are solitary creatures: their days are spent alone, with keyboards and pens under their fingers and a humming photocopying machine down the road at the university. Those things are real, and what one can do with them exciting, while websites, e-readers, and even books seem abstractions, mere mechanisms of distribution.

Jason Pontin is the editor in chief of MIT Technology Review.

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Heather Holmes, Senior Vice President of Audience Development

Breaking Down Walls of Sound

By altering the craft of how music is recorded, technology is actually renewing the social, ephemeral aspects that are experienced most fully in live performance.

By David Talbot

Since the invention of the phonograph 135 years ago, no performer has gone further than Glenn Gould to embrace music's transition from something ephemeral and experienced socially (whether in a forest clearing, chamber, or concert hall) to something recorded and experienced privately (whether on tape, CD, or MP3). Gould, the pianist best known for his mastery of Bach, was deeply uncomfortable with performing and quit it altogether in 1964, at 32. To him, the audience had become a kind of enemy that listened to see if it could spot mistakes. "The concert is dead," he declared. He turned, instead, to the purity of recording technology, because it offered full control over how a piece of music would be experienced. He would do take after take of Bach's *French Suites* or *Goldberg Variations* in search of the definitive, if spliced-together, rendering of his interpretation (which was necessarily subjective, as Bach lacked the modern piano).

Glenn Gould, seen with his coat hanging on a microphone stand in a New York recording studio in 1956, so preferred the control and precision made possible by recording technology that he eventually quit live performance entirely.

Gould, who died in 1982, was right that technology would transform the experience of music—just not in ways he could have foreseen. Technology does allow musicians to set down their idea of a perfect rendering, as Gould wanted. But as David Byrne, frontman for the 1970s and 1980s band Talking Heads, observes in his book *How Music Works*, technology is now making it possible for essentially anybody to make music and distribute it anywhere. Through this democratizing transformation, the value of a recording actually could be diminishing. Technology may in fact be making music a more, not less, social experience: it brings us back together to hear it played live.

How Music Works
David Byrne
McSweeney's, 2012

FEAR OF MUSIC

Gould was a hypochondriac who loathed to be touched, but his preference for recording was not as unusual as his personal habits. After his pronouncement, many musicians enjoyed a fertile period of innovation in record production. Just three years after his retirement from the stage, another act that had also quit touring finished a new album: *Sgt. Pepper's Lonely Hearts Club Band*. Released in 1967, it represented a huge technological leap. The Beatles and producer George Martin created a sort of virtual multitrack recorder by chaining four-track recording devices together (mixing down four tracks onto one track of another machine); made speed changes to voice tracks; added analog effects to instrument tracks; and doubled or tripled certain layers of sound. The Beatles never performed it live.

Soon after, the first digital synthesizers appeared. The 1970s and 1980s ushered in an era of specialized digital hardware, epitomized by the $200,000-plus Synclavier, one of the first products that allowed full digital manipulation, synthesis, and

TIME & LIFE PICTURES/GETTY IMAGES

editing of sound. Talking Heads was one band to take advantage of such tools. The group started as a spare, arty group at the New York City club CBGB. But with their third album, *Fear of Music*, they reached a new level of critical and commercial success. This was thanks partly to the production by Brian Eno, the former Roxy Music keyboardist who used more sound effects and processed instrument tracks than the group had done earlier.

Byrne then faced the tricky task of meeting audience expectations. He recalls loading the stage with new gear, including a Prophet-5 synthesizer, but recognizing the limits of the technology. "We could reproduce some of the more far-out studio sounds and arrangements we'd worked on, if only just, but we knew it was equally important to maintain our tight rhythmic core," he writes. "We were still a live performing band and not simply a group that faithfully reproduced recordings." Byrne didn't see his job as just making a recording, or playing a certain version live, but also as celebrating the social aspect of music. Still, back then the recording was still the way most people would experience Talking Heads. The fact was, record sales were where artists like Byrne made money. Touring had a business objective: to drive up interest in the record.

GAME CHANGER

That model persisted for 20 more years; CD sales peaked in 1999. But they soon crashed with the advent of digital file sharing. U.S. music sales in 2011, including digital downloads, totaled $7 billion, down from $14.6 billion in 1999.

Even as recording sales plunged, once-exotic technology for music making got cheaper and cheaper, and fell into the hands of more and more musicians. New software started doing what the Synclavier did. Garage Band, a music recording program that comes free with any MacBook Pro, includes sounds as good as those on once-cutting-edge gear such as the Kurzweil 1000 PX Professional Expander, a black box that musicians bought in the late '80s to play sampled instrument sounds from a separate keyboard. Websites like Samplebank allow artists to upload and swap samples and riffs for $99. The costs of mixing and recording plunged, and "now an album can be made on the same laptop you use to check e-mail," Byrne writes. He now works mostly in his home studio.

This made it far easier for musicians to get started. In 2005 Jonathan Coulton quit his job writing software and devoted himself to composing and recording catchy songs about suburbia, the workplace, and geek culture ("Shop Vac," "Code Monkey"). Coulton is known as a deft Internet marketer, but he credits technology more fundamentally—for helping him make the jump in the first place, and then for helping him craft his songs. "At some point the technology was so advanced that the demos I was making at home were as good as the final recording," he says. "So why would I make a demo? Why don't I just sell this?" He gets some ideas from the Kaossilator, a touchpad-controlled synthesizer that costs just $160. A swipe of your finger suggests scales, chord progressions, or drum fills. "In my phone, I have more power than the Beatles had when they made *Sgt. Pepper*," he says. "That is a real game changer, and I think we've really just scratched the surface."

SOCIAL ROOTS

There is a corollary to all these advances. With so much more music being made and consumed, it's harder for musicians to stand out. *Who Kill*, by Tune-Yards, won many critical plaudits as one of 2011's best albums. But compared with past critics' favorites, including *Sgt. Pepper* and *Fear of Music*, it barely sold: just 47,000 copies in 2011. This is why live performing—about the only thing, along with T-shirts, that can't be digitized—has become a musician's primary source of income.

Byrne remarks that the technology of music consumption—iPods and earbuds—hasn't actually changed what's been written. "If there has been a compositional response to MP3s and private listening I've yet to hear it," he writes. Instead, the more powerful force in musicians' lives is how technology is renewing the emphasis on music's social roots. Byrne, 60, says he's getting rid of LPs and CDs and venturing out of his Manhattan apartment weekly to see live acts. "There are other people there," he writes. "Often there is beer, too."

He sees the possibility that technology will increasingly bring us out to hear live music, turning Gould's ideas on their head. "A century of technological innovation and the digitization of music has inadvertently had the effect of emphasizing its social function," he writes. "Not only do we still give friends copies of music that excites us, but increasingly we have come to value the social aspect of a live performance more than we used to . . . The technology is useful and convenient, but it has, in the end, reduced its own value and increased the value of the things it has never been able to capture or reproduce."

As for Gould, it's still possible to watch him today, hunched over his keyboard. He's immortalized on YouTube, and watching him there inspired me to take a stab at the third movement of Bach's *Italian Concerto*. Gould would surely have found himself in strange company online. I hope he wouldn't have felt his devotion to technology was misplaced.

David Talbot is the chief correspondent of MIT Technology Review.

Demo

Super-Cheap Health Tests

A Harvard spinoff is making a liver test out of paper.

By David Talbot
Photographs by Ken Richardson

George Whitesides

Diagnostics for All, a nonprofit in Cambridge, Massachusetts, is making a test for liver damage that could cost just pennies. It consists, remarkably, of a stamp-size square of paper with wells that change color when a drop of blood is applied.

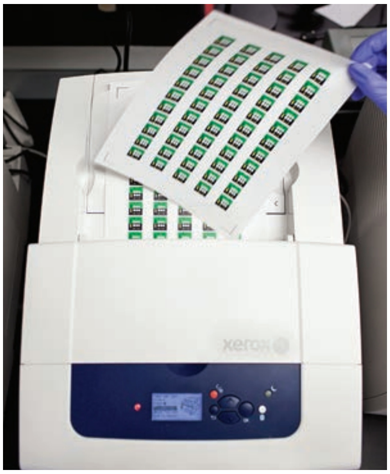
The test could provide an enormous benefit in poor countries, where liver damage is widespread as a side effect of drugs administered to HIV and tuberculosis patients. (As many as one-fourth of people taking antiretroviral drugs in the poor world develop liver problems—five times the rate elsewhere.) The liver function tests administered regularly in the developed world require tubes of blood, lab equipment, and electricity. The paper chip from Diagnostics for All needs none of that.

The test uses patterned channels and wells to allow for filtering and multistep reactions; the technology originated in the lab of Harvard chemist George

01 Paper is printed with wax to define zones for 55 tests. Each test measures two liver enzymes. Finished tests include a sandwich of two such sheets.

02 03 The sheets are baked for 30 seconds at 130 °C to allow the wax to melt completely through the paper's 0.2-millimeter thickness. The test wells are wax-free circles two millimeters across.

04 Measured amounts of the reactant chemicals are deposited on each of the two sheets. The first sheet gets reagents that react with enzymes. The second sheet (shown here) gets dyes that change color if exposed to products released by the first reactions.



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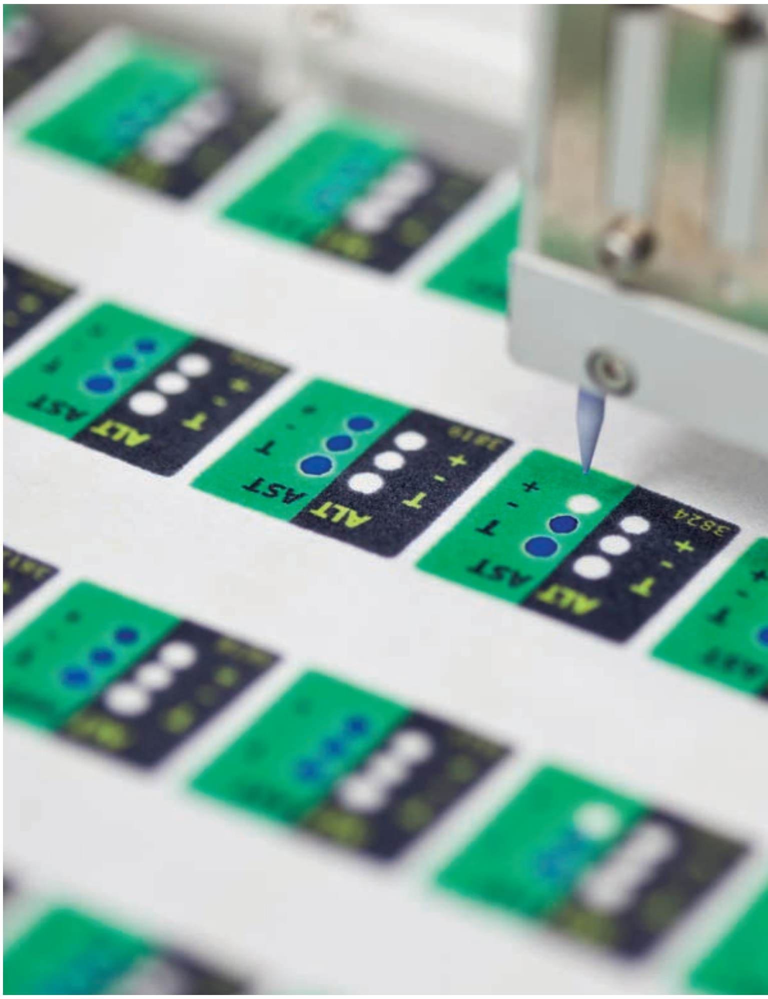
PORTRAIT: DAVID TALBOT/MIT TECHNOLOGY REVIEW



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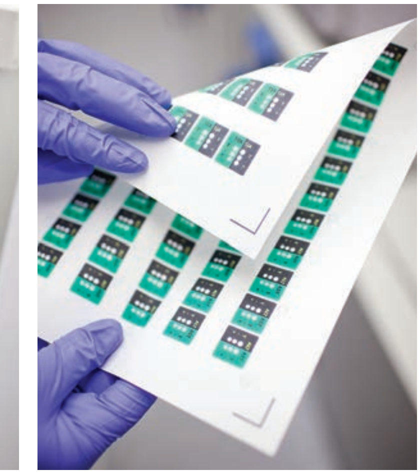

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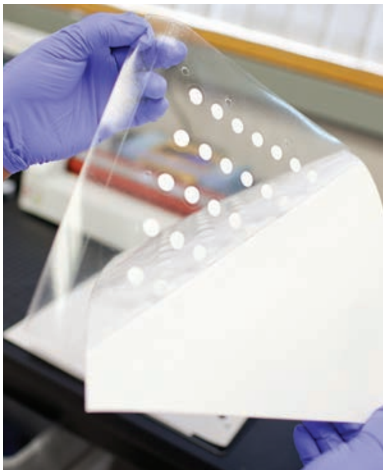
05 The two sheets are fused together with adhesives in a press.

06 An adhesive sheet with circular blood filters is prepared. Later, this sheet is affixed to the fused paper sheets. Only plasma reaches the paper layers.

05



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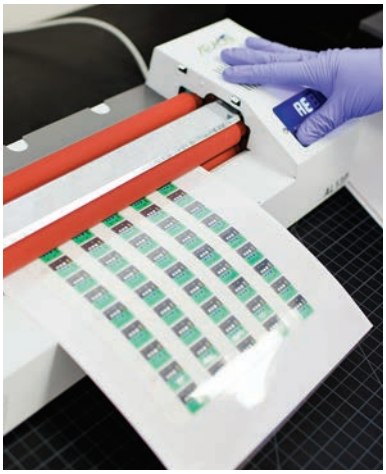
07
08 In a final step, a protective laminate is affixed to the top of the package, and the completed tests are cut into individual squares.



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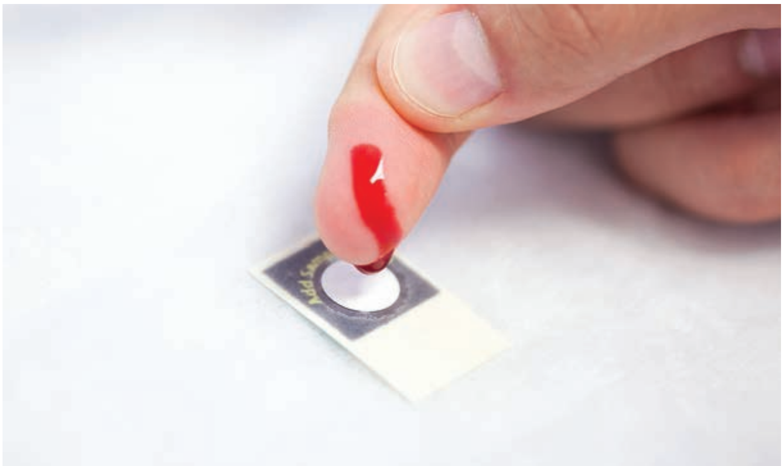
09 A drop of blood first encounters a plasma filter. The plasma then wicks through test wells on the two layers of paper.



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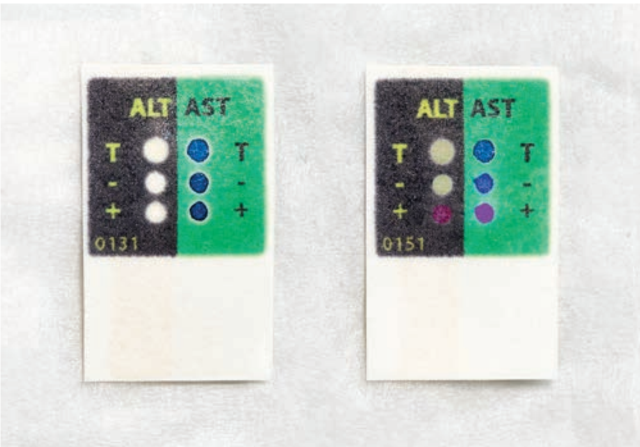

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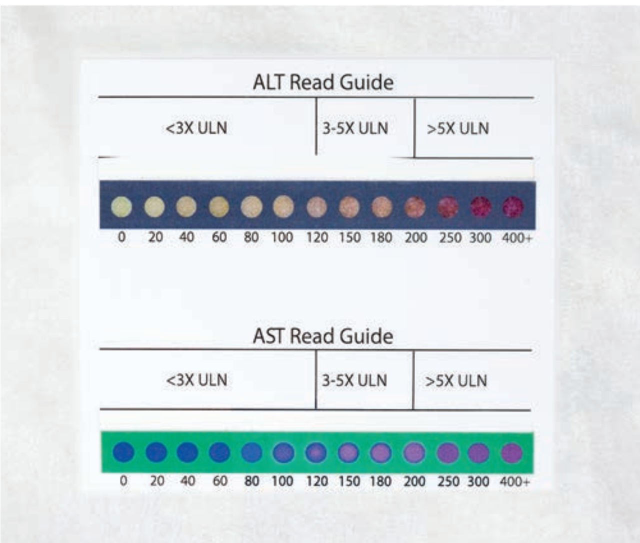


12

10 **Test results take about 15 minutes to appear. At left is the back of an unused test; at right, one activated with blood.**

11 **The results (right) show that the blood has normal enzyme levels, as indicated by the color in the top wells. The other four wells are controls that tell whether the test worked properly.**

12 **The scale in this guide offers a way to gauge the level of enzymes present. Clinicians could use this information to change a drug regimen or order additional tests.**

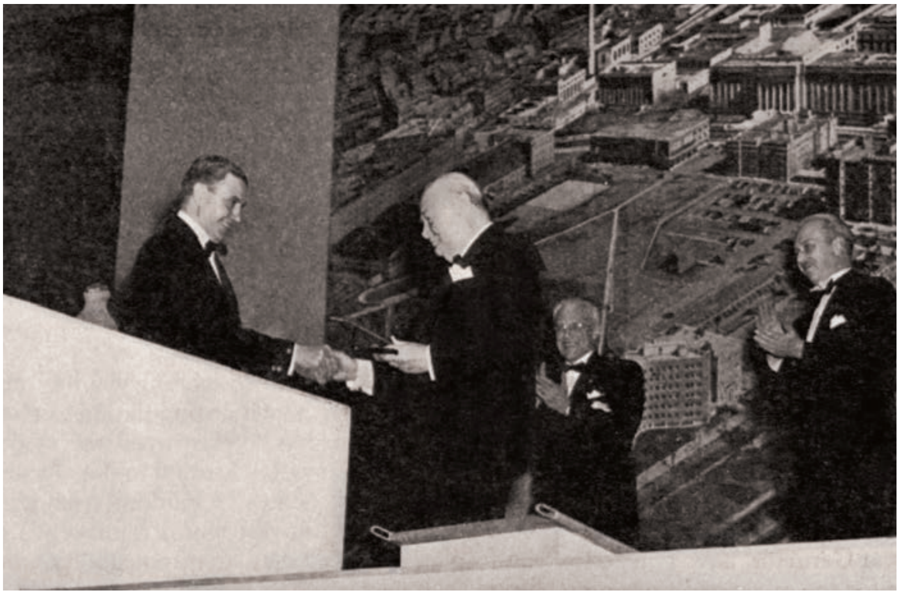
Whitesides, who pioneered this method, and was licensed from Harvard (see "Paper Diagnostics," March/April 2009). The paper absorbs sample fluids and uses capillary action to convey them to the test wells imprinted on it. These wells are spotted with chemicals that change color when they react with certain markers in a liquid.

The chip is meant to work simply with little additional equipment, making it suitable for the poorest regions. "This is a world in which there are very few resources—that is to say, almost no money, very few doctors, no electricity in many places, no refrigeration," Whitesides says. "The conditions are such that it's very difficult to imagine how you deliver even pretty straightforward health care."

Five years after the company was formed, Diagnostics for All, which is led by biotech executive Una Ryan and sustained by grants from the Gates Foundation and others, is moving toward a viable product. The first trial of the liver test is in progress on HIV patients at a hospital in Vietnam. Funding, manufacturing, and distribution models are still being worked out, but the company can make between 500 and 1,000 tests per day at its Cambridge facility and hopes to obtain regulatory approvals so that the liver test can reach patients by 2014, says Jason Rolland, who leads engineering efforts as the company's senior director of research.

DFA (as the company is known) is working on other paper-based diagnostics: an assay that detects antigens for multiple diseases, including malaria and dengue fever; a test for preëclampsia in pregnant women; and even nucleic-acid tests to detect pathogens in blood. The company is also developing tests that farmers could use to check for foodborne toxins. In all cases, results can be interpreted by a clinician or a smartphone app, after which test patches can be incinerated. They are, after all, just paper.

63 Years Ago



Before addressing the MIT community in 1949, Winston Churchill accepted an appointment as honorary lecturer from Institute president James Rhyne Killian.

Churchill's Warning

In a 1949 address published in these pages and excerpted here, Winston Churchill said new technologies create problems even as they solve others.

The outstanding feature of the Twentieth Century has been the enormous expansion in the numbers who are given the opportunity to share in the larger and more varied life which in previous periods was reserved for the few and for the very few. This process must continue at an increasing rate. If we are to bring the broad masses of the people in every land to the table of abundance, it can only be by the tireless improvement of all our means of technical production, and by the diffusion in every form of education of an improved quality to scores of millions of men and women. Yea, even in this darkling hour I have faith that this process will go on.

For us in Britain, the Nineteenth Century ended amid the glories of the Victorian era, and we entered upon the dawn of the Twentieth in high hope for our country, our Empire, and the world. In 1900 a sense of moving hopefully forward to brighter, broader, easier days predominated ... We took it almost for granted that science would confer continual boons and blessings upon us, would give us better meals, better garments, and better dwellings for less trouble, and thus steadily shorten the hours of labour and leave more time for play and culture.

Science presently placed novel and dangerous facilities in the hands of the most powerful countries. Humanity was informed that it could make machines that would fly through the air and vessels which could swim beneath the surface of the seas. Certainly it was a marvelous and romantic event ... This vast expansion was unhappily not accompanied by any noticeable advance in the stature of man, either in his mental faculties, or his moral character. His brain got no better, but it buzzed the more ... Our need was to discipline an array of gigantic and turbulent facts. To this task we have certainly so far proved unequal ...

Scientists should never underrate the deep-seated qualities of human nature and how, repressed in one direction, they will certainly break out in another. The genus homo—if I may display my Latin—is a tough creature who has traveled here by a very long road. His nature has been shaped and his virtues ingrained by many millions of years of struggle, fear, and pain, and his spirit has, from the earliest dawn of history, shown itself upon occasion capable of mounting to the sublime, far above material conditions or mortal terrors.

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